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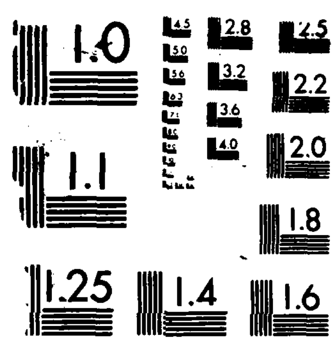

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DESIGN OF GPS STATUS REPORTING SYSTEM

THESIS

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DESIGN OF GPS STATUS REPORTING SYSTEM

THESIS

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Preface

The purpose of this study was to design a satisfactory status reporting system for NAVSTAR GPS. A systems engineering approach was used, and the focus was limited to a complete operational satellite constellation and navigation user requirements. The recommended system consists of a two tier database computed in real-time as the operational GPS constellation changes and a microcomputer program to customize outage information for extraordinary requirements.

In writing this thesis, I have had a great deal of help from others. I am indebted to my faculty advisors, Lt Col John Valusek and Dr. Darrel Hopper for their patience, guidance, and assistance. I also wish to thank Maj. Frank Zawada, and Maj Rudy Schwab at Space Command Plans for suggesting and sponsoring this effort. Finally, I wish to thank my wife Tricia and my children for their understanding, encouragement, and cooperation in allowing me to complete this thesis.

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Abstract

The purpose of this study was to design a status reporting system for NAVSTAR GPS. A systems engineering approach was used for the full satellite constellation with fully functioning user equipment. The recommended system consists of three main elements: a database, a status transmission mechanism, and microcomputer software. The database proposed has two tiers and is maintained in real-time as the operational constellation changes. The first tier contains the orbital ephemeris of the active constellation. The second tier consists of areas and associated times of degraded coverage.

Two methods of initial transmission of the status information are identified. The Notices to Airmen (NOTAM) system that currently exists is one primary transmission system. The other recommended initial link in the transmission process is electronic mail. Further dissemination by appropriate agencies using a variety of transmission methods is also outlined.

The final element of the system is software that can run on microcomputers. This software would allow users with special requirements to compute degraded coverage from the ephemeris data using assumptions and parameters different from those used in producing the second tier of the database.

DESIGN OF GPS STATUS REPORTING SYSTEM

I. Introduction

Background. Department of Defense policy in 1986 calls for NAVSTAR GPS to become the primary DOD radio navigation system. Therefore, accurate dissemination of system status information is critical. Sound operating practices and FAA tasking require establishment of procedures for informing users when the navigation capabilities available from GPS become degraded. Air Force Space Command will have control responsibility for GPS and is studying ways to integrate it with existing navigation operations.

In the early 1990's, the satellite based NAVSTAR GPS will provide all-weather world-wide navigation for air, land, and sea use with accuracy not available by any other means. Initial Operational Capability (IOC) was scheduled for 1989 prior to the January 28, 1986 shuttle Challenger accident, but because of the present launch vehicle crisis, it appears that date will slip a minimum of two years. Military planners continue to actively address operational issues involved with GPS employment, and this research project is part of that effort. Specifically, this thesis presents a status reporting system for navigation users.

GPS is a US Defense Department developed system that consists of three segments: a space segment, a control segment, and a user segment. The space segment is made up of 18 operational and 3 active spare satellites in 6 circular, 20,600 KM, 55 degree inclined orbits broadcasting precise position and time information on 2 L-band frequencies. The control segment consists of a master control center, dispersed monitoring stations, and dispersed transmission stations to accomplish satellite updating and housekeeping activities. A wide variety of user equipment, specialized for individual needs, makes up the still evolving user segment. A Nuclear Detection Payload with the capability to provide very accurate nuclear detonation information to military commanders also flies on GPS satellites. While GPS is a DOD system fulfilling military navigation related requirements, it is expected to have widespread civilian uses. Figure 1 represents an overview of the total GPS system.

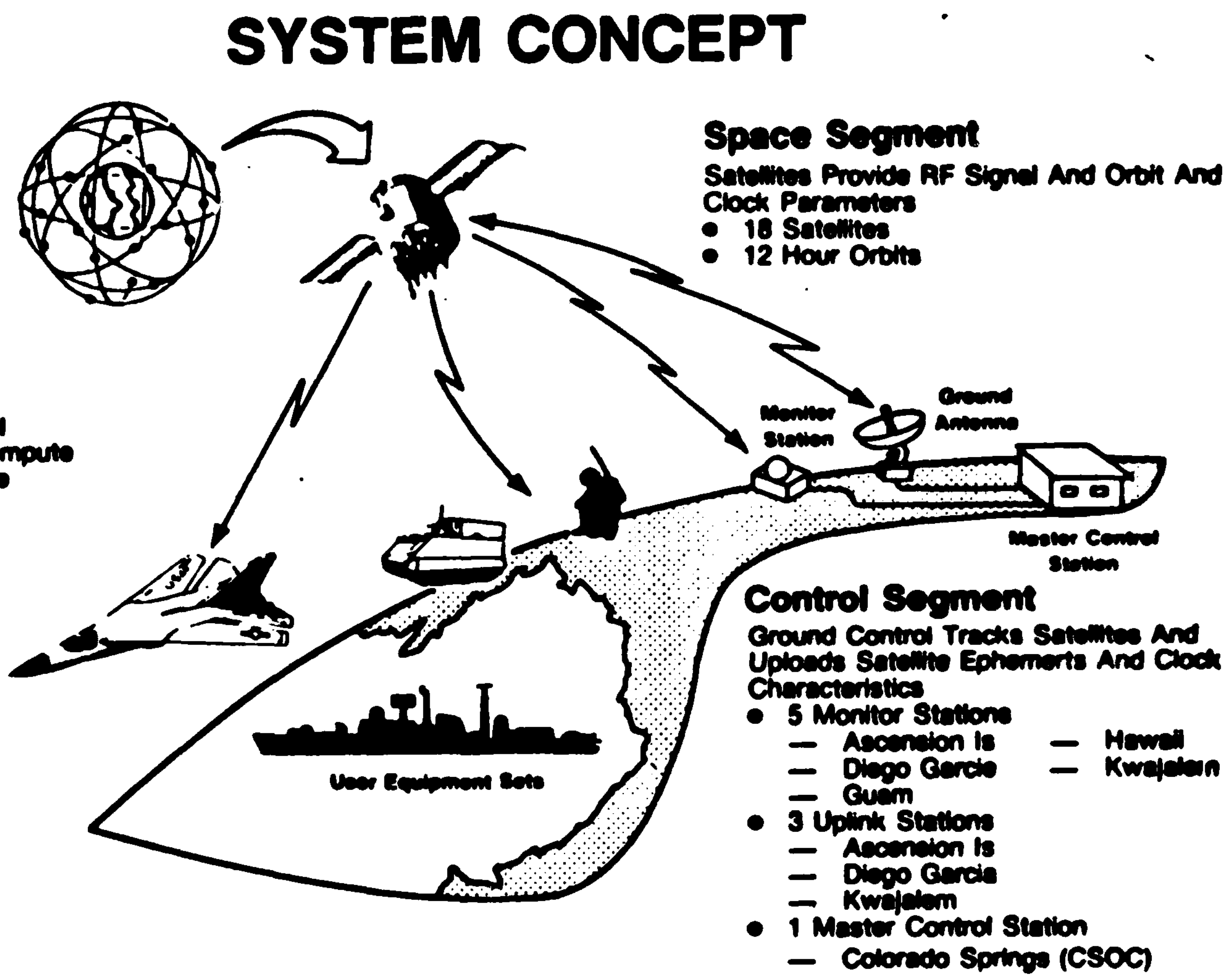

Figure 1. GPS System Concept (Parkinson, 1983:1190)

One of the two GPS modes is the Precision mode (PM). It provides targeting quality accuracy for military operations and is accessed through a classified code. A second course mode (CM) provides navigation information to any user possessing appropriate receiver equipment. Test results of nominal CM accuracy in the 55 meter range prompted DOD to provide a detuning capability on operational satellites. Controversy still surrounds this purposeful degrading of accuracy that has come to be known as Selective Availability (SA). But even at 100 meters, the currently proposed setting, GPS represents a quantum improvement in accuracy for many applications compared to existing navigation aids. Normally, GPS receivers automatically select four satellites in the sky to calculate three-dimensional position and time. For each known quantity, one less satellite is required to determine the remaining parameters. For example, if altitude is known, as with a ship (sea level), only three satellites are needed. With all 18 satellites, there will normally be at least 5 satellites available for use at any position on the earth.

The number of satellites "visible" to a user is a function of mask angle, defined as angle above the local horizon below which signal errors due to refraction degrade signal usefulness. Another factor that affects GPS accuracy is the geometry of satellites. Position Dilution of Precision (PDOP) is a common measure of the effects of this

geometry. PDOP is defined as the ratio of the root mean square (r.m.s.) position error to the r.m.s. ranging error from all satellites (Kruh,1981:E9.3.2). For typical assumed values, mask angle of 5 degrees and PDOP of less than 6, four satellites are useful 99.5% of the time (Kruh,1981:E9.3.2). These assumed values are based on stringent military specification for which GPS is being designed. The 99.5% figure does not consider the three active spares that are currently planned to provide additional redundancy in CONUS.

The robustness to failure of a single GPS satellite differs from current navigation aids, where failure of any aid significantly affects users until the system returns to service in at least some limited geographic area. In the case of GPS, a single satellite failure will likely result in poor navigation geometry for some short period of time at any given location. These periods of poor satellite geometry or insufficient visible satellites vary with the specific satellite or satellites that have failed. Therefore, it becomes questionable whether just reporting individual satellite losses to navigation users provides the required, useful information.

Problem Statement. A satisfactory status reporting system is required to implement GPS based navigation.

Research Objective. Determine an acceptable method of measuring NAVSTAR GPS status for navigation use and identify satisfactory systems for reporting status to users.

Subsidiary Objectives. The determination of measurement criteria that emphasizes safety, while offering operational capability when the GPS system is functioning satisfactorily, requires analysis of three subordinate aspects of the problem. First, what are the requirements currently established for navigation systems and how does GPS measure up to these requirements? Requirements vary depending on the phase of navigation being considered. Secondly, what degree of constellation degradation constitutes a system that makes it unreliable for navigation? Questions in this area include the following:

1. Is PDOP the correct measure of merit to take into account satellite geometry? If so, what is the appropriate maximum PDOP value that is acceptable for good navigation fixes?

2. What mask angle (elevation angle) should be used to consider a satellite visible?

3. Are different mask angles appropriate for different navigation applications?

4. Is there a minimum time period of no satellite coverage that is acceptable to navigation users, and if so, what is a reasonable time period below which to discount an outage? Is this acceptable outage period application dependent?

When these questions are addressed, it will be possible to evaluate how best to disseminate system degradation to users in a simple, familiar manner.

Scope, Limitations, & Assumptions. Many ancillary uses of GPS have been proposed, including time transfer, hydrographic surveying, and spacecraft navigation. Some of these implementations are already in operation using the

limited constellation of prototype satellites currently in orbit. However, the present research is concerned only with the normal navigation capability provided by GPS. This assumes a low threat jamming environment and does not specifically address the weapons delivery aid or test range instrumentation potential of GPS.

Furthermore, this thesis is to focus on a GPS system after initial buildup of the constellation and not the interim period prior to initial operational capability. Finally, a fully functioning control segment is assumed with the capability to regularly update navigation data.

Methodology. A systems engineering approach using the Hall activity matrix as a guideline is the basic approach for this research (Sage, 1977:5). The effort will focus on the Project Planning phase of Hall's structure. To achieve the stated objective of this research, it is necessary to determine measurable objectives and systematically compare generated alternatives. Chapter three is dedicated to the details of the process which is followed.

Organization of the Report. Chapter one has been concerned with background information and an overview of the scope and approach of the analysis. In chapter two a summary of the issues found in the technical literature and a description of several in-place navigation aid status reporting systems is presented. Chapter three describes in detail the systems engineering approach used in this analysis

as well as the results of the first four steps in the process. A model GPS status reporting system is described in chapter four with specific parameters chosen for major elements of the system. This model was tested by sampling navigation users with a questionnaire, and the results are presented in chapter five. Chapter six deals with the conclusions of the analysis and ideas for future work that may be valuable in this area.

II. Current Environment

This chapter presents the current views found in the literature on topics relating to a GPS status reporting system. It then discusses ways being used in 1986 to report the status of a sample of radionavigation aids. The literature points out considerable controversy over issues directly related to status reporting along with a wide range of views on exactly how GPS implementation will proceed. The current status reporting information was compiled primarily from review of directing regulations and interviews with individuals actually responsible for disseminating that information. Some assessments of status systems is also based on the author's world-wide aviation experience.

Literature Review

One of the most important considerations for understanding the requirements of a GPS status reporting system is the requirements of current navigation aids. The Federal Radionavigation Plan (FRP), 1984, a joint Dept. of Defense/Dept. of Transportation plan, outlines present radionavigation systems and their requirements as well as factors considered important in selecting future systems. It divides uses into the four broad categories of air, sea, land, and space, and then subdivides these into several different phases. GPS is the most versatile system discussed in the plan because it has the potential for providing future

navigation to all users in every area except terminal precision approach guidance for aircraft (FRP:I-22).

The plan further describes major factors for evaluating navigation aids. These are accuracy, availability, coverage, reliability, fix rate, fix dimension, capacity, and ambiguity potential. Once again, all systems except GPS have serious deficiencies associated with at least one of these factors which limits its usefulness (FRP:III-32).

Optimism about the capabilities of GPS by military planners is perhaps best illustrated by the following statement: "It is the goal of the DOD to phase out use of TACAN, VOR/DME, OMEGA, LORAN-C and TRANSIT in military aircraft and other platforms" (FRP:I-9). This list represents virtually all radionavigation aids DOD currently relies on, with the exception of ILS/MLS which is used for precision approach guidance. Widespread civilian use of GPS is also anticipated (FRP:I-37) (Degoot, 1984:23) (Gregory, 1985:57-59). This diversity of users creates a status dissemination task of unprecedented scale.

One key area of concern outlined in the FRP in connection with GPS certification as a "sole means of air navigation" is coverage (FRP:I-9). With a single satellite failure, there is some small but finite time when four well-placed satellites are not available. PDOP is the most popular measure to account for poor satellite geometry. The terms Geometric Dilution of Position (GDOP), which includes

time error, and Horizontal Dilution of Position (HDOP), which considers only two dimensional position are also seen. In all cases lower is better, but there is a range of assumptions about how high is acceptable. Much of the literature assumes loss of coverage over any area that has a calculated PDOP above six (Kruh, 1981:E9.2.3) (Knable and Kalafus, 1984:290). This assumption is made in spite of FAA test results that show accuracy that meets FRP criteria for all but precision approach use with higher PDOP values (Connor, 1982:C1.1.5). Clearly, further analysis of data is needed on how PDOP values correlate to GPS accuracy, which in turn determines when the system provides sufficient coverage.

Another coverage-related question has to do with the lowest acceptable position in the sky from which a satellite can be used for navigation. This figure is most often given as a "mask angle", which is the the angle above the local horizon. Originally, designers planned on a 5 degree mask angle, and the analysis of at least four satellites in view 100% of the time is based on this 5 degree value. With a mask angle of 10 degrees, at least 4 satellites are in view only 99.98% of the time (Kruh, 1981: E9.3.7). The FAA has indicated that 7.5 degrees may be the correct figure, while loss of coverage is also explained using 8 and 10-degree mask angles (Knable & Kalafus, 1984:294). Rationale for the use of any specific value is generally absent from the literature. However, it should be noted that the variations

in assumptions have a large impact on the expected coverage should a satellite be lost. Table 2-1 illustrates the differences for different mask angle assumptions for a typical location with a nominal constellation and one SV out of service. Specifically, the location is New York City, and the calculations were made using a computer program called ZPDOPG with satellite vehicle (SV) number one out of service (ZPDOPG, 1985).

Table 2-1

Degraded Coverage as a Function of Selected Mask Angles

Mask Angle	Number of Degraded Times Each 24 Hours	Total Duration of Degraded Coverage Each 24 Hours
5 Degrees	2	35 minutes
7.5 Degrees	5	3 hours
10 Degrees	7	4.5 hours

Integrity of the GPS system is the other factor of GPS that the FRP questions (FRP:I-9). This has to do with a requirement to provide a positive indication to the user of system failure within 10 seconds of it's occurrence (Braff & Bradley, 1984:309). As explained by Braff and Bradley in a Mitre/FAA paper, GPS has some integral monitoring which functionally turns off the transmitted signal if it is determined to be in error by internal circuitry. It does not, however, have a system for testing the signal after it leaves the transmitter, which is a feature of the current

international standard for air navigation, VOR (Braff & Bradley, 1984:307). The absence of this test of the "signal in space" which is considered the "ultimate integrity" check of the VOR system is viewed by some as a property that disqualifies GPS as a legitimate "sole means of air navigation" candidate in its present form (Braff & Bradley, 1984:309).

The 10-second criteria is based on the most critical scenario of a pilot flying a non-precision approach using GPS who receives a faulty signal not detected by the internal fault system. In this situation, there is not a positive indication (typically an off flag in the receiver) in sufficient time to allow the pilot to take appropriate action. The Multiservice Initial OT&E of NAVSTAR GPS User Equipment Final Report recommends modification of current user equipment computer logic to reject erroneous satellite signals using more strenuous standards (AFOTEC, 1986:9). As the present system is envisioned, the control segment would have to uplink a command to the satellite to cease transmission, and the time required for this sequence of events to take place is on the order of 15 minutes (Braff & Bradley, 1984:309). A variety of other solutions to overcome this problem have been studied, but they generally require significant costs to implement (Klein & Parkinson, 1984:303). Many of these "enhancements" to the GPS system also address increasing accuracy of GPS in a Selective Availability

environment using pseudo-satellites, commonly referred to as differential GPS (Kalafus and others, 1983:187).

From the above discussion of PDOP, it should be clear that the time the system should be considered unreliable is an open issue. With the currently planned 18 satellite system, there are always at least 4 satellites in view, and coverage is lost solely as a result of large PDOP. (Kruh, 1981:E9.3.7) Another source of system degradation that is identified by the multiservice IOT&E of user equipment is the improper uploading of ephemeris, clock bias and/or almanac data from the control segment (AFOTEC, 1986:9). While an operational control segment should greatly reduce these degradations, test results showed that incorrect satellite data "caused significant loss of operational capability due to degraded navigation information and/or GPS user equipment failure" (AFOTEC, 1986:9). User equipment software modification is also being pursued to detect this problem.

A final consideration is the requirement to provide a three dimensional position fix. No current enroute air navigation system provides three dimensional position, and there are several techniques employed by user equipment to provide good two dimensional position accuracy with fewer than four satellites available.

Use of an accurate clock and input of non-satellite derived altitude information are frequently cited as methods

of providing users with accurate navigation information when less than four satellites are providing correct signals. Sturza examines navigation using GPS and a precise clock and concludes that suitable navigation can be performed by this method (Sturza, 1983:155). Knable and Kalafus discuss "clock coasting and altimeter aiding" and also conclude that accurate clocks and encoding altimeters are available to provide needed information to the GPS receiver, but they remark that the cost of such equipment is still rather high (Knable and Kalafus, 1984:289-301). These results are important because they broaden the view of what degree of system degradation is appropriate for status reporting. The results also influence the time constraints for reporting outages.

Integration of GPS with other navigation systems is another alternative for building additional redundancy into GPS navigation. Inertial navigation systems (INS) are the predominant ones being considered as integration candidates. Navigation system integration is an operationally mature approach to getting the most from a group of systems. Wiederholt and Klien review several synergistic effects of interfacing GPS with other navigation platforms as a method of insuring accurate navigation information when the required numbers of useful satellites are not available (Wiederholt and Klein, 1984:129-151). They take a generic approach to the integration argument while Schwartz specifically

addresses GPS/INS interface, again finding very encouraging results (Schwartz, 1983:325-337). It should be noted that initial military installations of GPS equipment will feature integration with INS systems for the F-16, B-52, F-111, A-6, and submarines. The UH-60 helicopter will integrate its GPS equipment with doppler radar.

While military applications do come under some scrutiny from the FAA and Coast Guard in their respective areas of safety responsibility, some flexibility seems to exist compared to civil applications. In the civilian sector, a special committee of the Radio Technical Commission for Aeronautics (RTCA) - SC 159 is actively pursuing Minimum Aviation System Performance Standards for GPS, with a draft in circulation (RTCA, 1986:A2.1-A2.7).

Methods of Distributing Radionavigation Status Information

This section describes the current procedures used to disseminate navigation aid status of important systems that are related to the GPS problem.

TRANSIT. TRANSIT is a US Navy satellite based system used for world-wide maritime navigation. When a satellite problem occurs, the Naval Astronautics Group, the controlling agency, sends out an autodin message to approximately 175 ships and over 100 other addressees consisting mainly of military command centers. The DMA hydrographic office is also an addressee, and it formats the message for an hourly radio broadcast message on the world-wide navigation warning

system. Approximately 50 messages a year are generated for both scheduled and non-scheduled satellite outages.

<u>OMEGA</u>. OMEGA is a US Coast Guard administered VLF world wide marine and air navigation system consisting of eight dispersed transmission stations. Some information on status is published in AIM Class II NOTAMs. For example, the Jul 3, 1986 AIM lists the North Dakota OMEGA Station out of service from 7 Jul to 30 Jul from 2000Z to 2400Z in the general remarks section of the Class II NOTAMs. AIM also publishes a Coast Guard phone number for current OMEGA information. There is apparently very little control of overseas stations regarding status reporting.

<u>VOR</u>. VOR is the International standard for short range air navigation. Within the CONUS, VORs are automatically monitored using a remote monitoring system with a warning sent to the responsible flight service station (FSS) or military operations center when an out-of-tolerance condition is detected.

Standard procedure is to confirm system outage with at least two aircraft operating in the vicinity of the VOR and attempting to remotely reset the system before initiating NOTAM action. This practice results from the fact that the alarm indicates a malfunction in the monitoring line indistinguishable from an actual navigation aid problem. Once a system failure is confirmed, the FSS issues a NOTAM through the FAA automated NOTAM system, and it is available

to users nationwide within several minutes. The entire process takes less than 15 minutes on average.

By international agreement, virtually every country in the world is responsible for maintaining a similar type of VOR reporting system. In practice, there is a wide range of interpretation and compliance, with US operations being the high-quality standard. The economic development of a specific country, in general, directly reflects the sophistication of their national airspace system. As one might expect, Western European and Japanese facilities are generally well maintained, and outages are reported in a timely, systematic manner. As one proceeds to less developed areas of the world like Africa, a more ad hoc approach to detecting and reporting system outages is the rule.

TACAN. TACAN (Tactical Air Navigation) is strictly a military system providing line of sight aid similar to VOR with distance measuring equipment (DME) as an integral feature. Outages are normally reported through theater military NOTAM systems. Since many North American facilities are combined VORs and TACANs (VORTACs), information concerning these facilities is available from either the FAA NOTAM system or the military system. As the current military NOTAM system in the US is phased out in the next several years, all reporting and information will be through FAA channels.

LORAN-C. LORAN is a long range aid originally developed for maritime use but becoming increasingly popular as an air navigation system. Outages are reported through the Notice to Mariner system. Coast Guard radio broadcast of unplanned outages is the most immediate form of this information to mariners.

FAA involvement with LORAN is a recent development, and they are moving to incorporate LORAN into the National Airspace System. They have not developed any standardized procedures of reporting system status for aviation users. The first FAA approved LORAN non-precision approach was commissioned in 1985 at Boston's Logan Airport. Approval to use the approach is contingent on the Air Traffic Control Tower personnel monitoring a good LORAN signal. FAA approval for LORAN approaches at up to 80 airports by the end of 1987 is anticipated, with 400 as candidates for eventually establishing such approaches.

Conclusion

Review of the literature on how GPS fits into the overall navigation system is important for understanding the complexities of designing a status reporting system. Terminology related to GPS orbital characteristics and how experts expect them to relate to navigation performance are also relevent to the status reporting design problem. An extensive body of literature discussing enhancements to a stand-alone GPS concept also exists. Some of these ideas are

presented to illustrate the dynamics of the GPS environment in which the status reporting system design effort was attempted.

The substantial infrastructure that exists for reporting current status information was reviewed. The purpose of this was to show that integration of GPS into existing systems promises benefits of user familiarity and cost savings. It also illustrates that GPS has unique features that differentiate it from any current system.

Th methodology used in attacking the research problem is explained in detail in chapter three. In addition, the initial steps in the process are applied to the status reporting problem.

III. Methodology

An overview of the systems engineering approach used to address the problem of designing a suitable GPS status reporting system begins this chapter. Following the overview, is a detailed discussion of the first four steps in the systems engineering process as they apply to the status reporting status problem.

Overview

' systems engineering approach, based on Hall's activity matrix for systems engineering , is used to develop a suitable GPS status reporting system. (Sage, 1977a:5). This approach was chosen as an accepted standard in the field of systems engineering (Sage, 1979b:499-503). This project is assumed to be currently in the Project Planning phase. The seven steps Hall suggests to provide a framework of systems engineering are as follows:

1. Problem Definition
2. Value System Design
3. System Synthesis
4. System Analysis
5. Optimization
6. Decision Making
7. Plan for Future Action

Each of these steps is addressed in this paper.

In the first step of problem definition, the exact nature of the problem is identified and scoped. Needs, constraints, and alterables are identified and related. The problem is partitioned, and subjective elements are isolated chiefly

by assumptions.

The second step is value system design, where objectives are defined, ordered in a hierarchical structure, and related to the needs, constraints and alterables of the problem definition. Additionally, measurements for the objectives are established so that one can evaluate how well the system achieves the stated goal of developing a suitable status reporting capability.

The next step in the process is system synthesis. Here the concern is with identifying alternative approaches to status reporting. A good description of the alternatives greatly enhances the efficiency and accuracy of efforts in later steps, and is thus an important aspect of the system synthesis step. Determining how each alternative will be measured essentially completes this phase.

The stage is now set for developing the models to be used in evaluating alternatives using the objective measurement criteria, which is done in the system analysis step. Models are developed with the intent to capture the essential elements of the system. Models accurately describe the system as it relates to the problem at hand so that alternatives can be judged in a systematic manner.

Optimization of alternatives is the next step, and limiting the number of alternatives to those that are not dominated in terms of objective measures is the goal. The concept of the nondominated solution set is helpful in

understanding this step. Further consideration needs only to be given to those alternatives that have at least one objective measurement that is greater than another alternative. An aggregate comparative approach to assessing some objective measurements is used in this analysis while a quantitative estimation is developed for others.

Decision making follows in the framework, and here decision maker preferences are considered. It is assumed that the key elements in establishing decision making preference in this problem are the perceptions, desires, and opinions of the users of the system being developed. A survey was used to measure these factors so that alternatives can be compared. The survey's purpose is to provide user feedback to help decision makers in choosing among those alternatives that were not eliminated in the systems analysis step.

One completes a phase of the Hall process by planning for future actions. This includes documenting the work that has been done and presenting results in briefing form.

Problem Definition

The first step in each phase of the systems engineering structured approach to problem solving is to clearly define the problem. A technique to aid in this process is to list the needs, constraints, and alterables of the system to be designed. The needs of the system are those functions

or capabilities desired in the system being designed. Constraints are those design parameters over which the system engineer has little control. Alterables are those parameters that the designer can control to a significant degree. The needs, constraints, and alterables of a GPS status reporting system as they are currently understood are listed as follows:

<u>Needs</u>.

1. Inform all navigation users of GPS satellite vehicle (SV)anomalies that will affect their ability to navigate using GPS.

2. Provide system status in a timely manner so that alternative courses of action can be evaluated during mission planning.

3. Be easy to learn and use.

4. Easily administered, maintained and modified as related navigation systems evolve.

<u>Constraints</u>.

1. Minimize cost and manpower requirements consistent with providing adequate service.

2. Requirement for modification of user receiver equipment to automatically determine current and future poor navigation solutions is not practical.

3. There are a wide variety of GPS users dispersed globally.

4. Limited telecommunications capabilities.

5. Status system should identify GPS status that will cause navigation solutions with errors larger than established criteria for respective phases of air and marine navigation as put forth in the FRP.

Alterables.

1. The level of detail in terms of time and geographical area for which to report.
2. Methods for disseminating status information (NOTAMs, radio broadcast, bulletin board, FLIP/AIM, combinations).
3. Format of status information (text, graphics, voice, combinations).
4. What higher status requirements above those of the FRP should be reported, and at what detail? Three dimensional "degraded" coverage versus the two dimensional requirements as described by the FRP.
5. Should selective high priority users have real time contact with the Master Control Center at critical periods of a mission in addition to the basic system service provided?

Value System Design

In the value system design step of systems engineering, the task is to develop objectives related to the needs, constraints, and alterables of the problem definition step. Typically, objectives are structured from general to more specific, with the most specific objectives allowing for quantitative evaluation during system analysis. Listed below are the objectives of a GPS status reporting system:

Objectives.

1. Design a satisfactory GPS status reporting system.
2. Minimize life cycle cost of the system.
3. Minimize the peak and average manpower requirements to implement the system
4. Maximize speed of dissemination of status changes.
5. Maximize the number of users with reasonable access to status information.

6. Provide sufficient detail of the system status to allow well informed navigation planning decisions.

7. Make the system as simple as possible to interpret.

Figure 2 represents a hierarchy of how system utility and costs are analyzed with the most specific factors addressed in measuring alternatives.

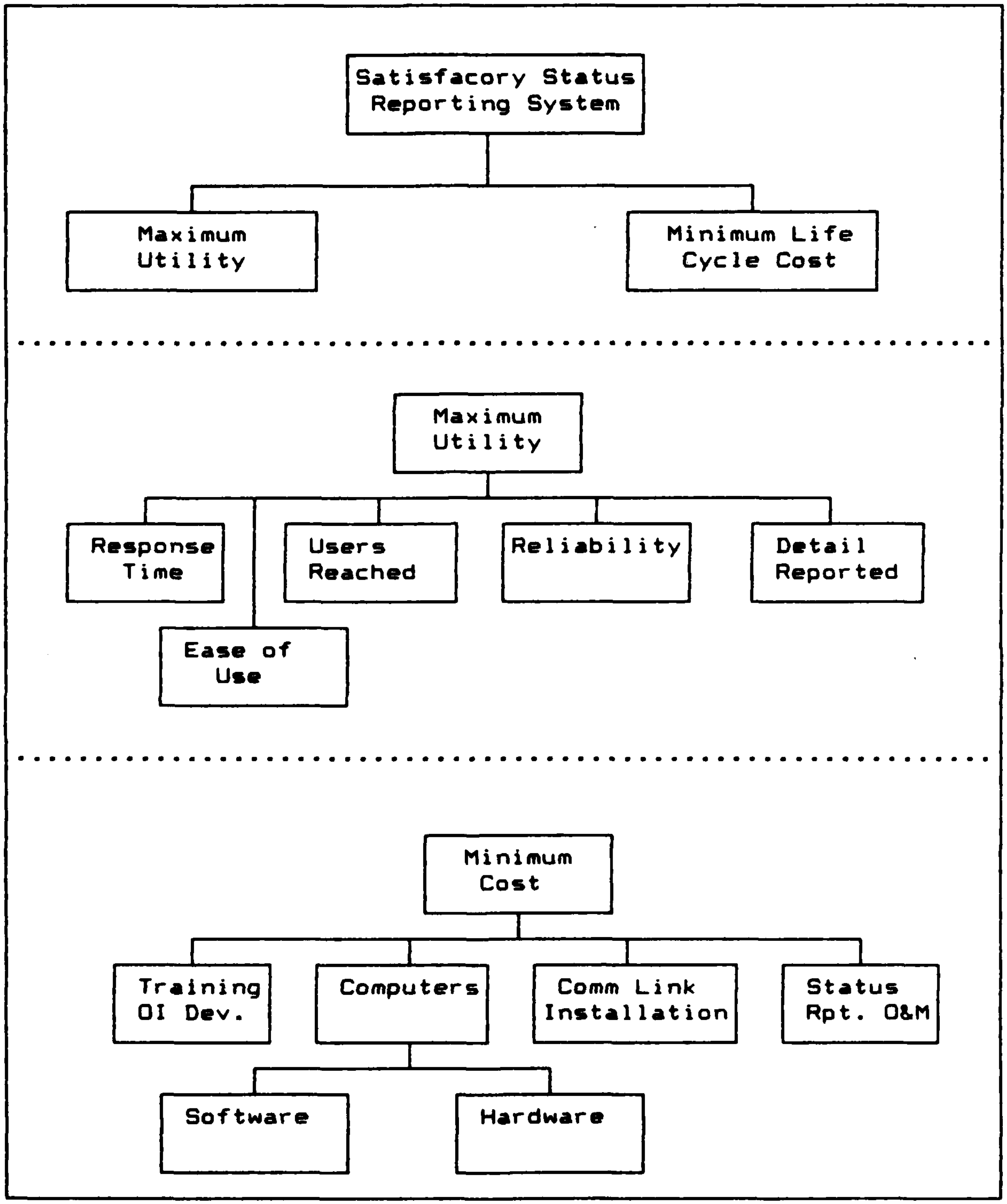

Figure 2.

Objective Hierarchy, General to Specific

Several measurements are not self evident and are considered as described here. Reliability is rated as high where the expected reliability is as good or better than the current methods of disseminating safety-related information. Unproven systems or systems that rely on links prone to unavailability are rated correspondingly lower. In the area of ease of use, those systems that present outage areas and times directly are rated high. Those systems that require cross referencing and table entry to determine degraded coverage are rated medium, and those systems requiring actual hands-on computer use are rated low.

In rating the level of detail reported, systems that allow specific parameters to be selected in determining outages are rated high. Those that have limited capacity for storing or transmitting outage information are rated medium. Systems that also must provide for an extensive list of possible combinations of outages are rated low.

<u>System Synthesis</u> (Alternatives)

Alternatives were developed to satisfy the system design problem of a workable status reporting system. Alternatives were developed from prospective reporting means found in preliminary studies, suggestions by AF Space Command personnel, and brainstorming in the conduct of this research. While possible solutions are necessarily open ended, this list represents the range of known, short-term alternatives being considered. The alternatives addressed in this paper

are listed below:

1. Narrative NOTAM/Notice to Mariners (ANMS)

2. Simple NOTAM/ANMS with reference to supporting document

3. Simple NOTAM/ANMS with data base query

4. Bulletin board

5. World wide radio broadcast

6. Autodin Message

7. Microcomputer software and a simple notice mechanism

8. Some combination of the above

A more detailed description of each alternative is discussed in the following section.

Alternative #1. Publish a narrative NOTAM/ANMS describing coverage problem areas each time a navigation message from an SV is in error. For example: "NAVSTAR satellite # 17 out. Area from 20W to 60W and 30N to 50N not suitable for GPS navigation from 070024Jul to 100024Jul, etc. etc.."

Alternative #2. Publish a simple NOTAM/ANMS and develop a reference FLIP/AIM document for users to look up what effect in terms of SV visibility and geometry they can expect. For example: "NAVSTAR SV #17 out, refer to GPS outage tables in an appropriate supporting publication." While the geographic area affected by a specific satellite outage is a constant value, the time of the degraded service changes by approximately 4 minutes each day. This would require a Julian day conversion calculation to be

incorporated into the tables.

FLIP Documents are managed by the Defense Mapping Agency (DMA) and the National Oceanic and Atmospheric Administration (NOAA) and distributed and updated at regular intervals to a wide range of operations centers. Commercial publication of the information contained in FLIP is also available.

Alternative #3. Publish a simple NOTAM/ANMS and provide a database for reference by geographic area as to what affect a specific SV or combinations of SV outages would have on an area. The FSS, base operations, or Coast Guard district office could then query the database for information on degraded coverage. A time correction for the current day would be made automatically, and the outage times would be available directly.

Alternative #4. Set up a bulletin board type service that contains GPS system status. This can be accomplished either by using existing military or commercial bulletin boards. Outages could be reported directly, or constellation status could simply be posted.

Alternative #5. Radio broadcast GPS system status. Several broadcast services currently exist mostly related to dissemination of weather information for both aviation and maritime users. Since the amount of information that can be transmitted by this means is rather small, in all likelihood some other medium would also be required to support this system. One such radio system is the world-wide navigation

warning system (WWNWS), administered by DMA.

Alternative #6. Use an autodin message to major theater command centers and federal agencies (FAA, Coast Guard, DMA) detailing outages. Allow them to develop more specific dissemination procedures that are customized for their area of concern and the types of operations for which they are responsible.

Alternative #7. Use any short notification method with microcomputer software to calculate degraded coverage due to satellite outages. The software should be made commercially available for use by the military and civilians and run on several different popular microcomputers. This microcomputer software would allow customizing outage parameters like mask angle and navigation accuracy threshold to other than selected default values.

Alternative #8. Use a combination of some or all of the above methods.

Systems Analysis

Before discussing the above alternatives in terms of meeting the established objectives, two points are worthy of reemphasis. First, this system is designed to provide planning information and not real-time notification. When a satellite being used for navigation actually becomes unreliable, user equipment should indicate this so that appropriate actions can be taken. Second, problems with the constellation requiring a SV to be considered out of service

are expected to be very infrequent occurrences. Historical satellite reliability indicates a major anomaly causing loss of the system occurs, on average, once every 100 days (Kahn, 1985:B-7). With the experience gained with developmental GPS satellites, Joint Program Office personnel expect an even lower anomaly rate (Connoly, 1986:interview). Furthermore, in the vast majority of cases, these problems are expected to be corrected within 12 hours of occurrence.

To facilitate identifying all the combinations of possible alternatives, two components required of all systems are paired. First there are three options identified for computing degraded coverage, or outage areas. These are as follows:

1. A centralized computation that directly reports outage areas and times.
2. A precomputed set of possible outage combinations published and distributed in book or disk form.
3. A microcomputer based system to allow dispersed organizations to calculate outages for their needs.

Second, there are different methods available to transmit outage information. Some methods are compatible with any computational option while others are suitable for only a subset of the computational options. The transmission methods considered here are as follows:

1. Notices to Airman (NOTAM).
2. Automated Notices to Mariners System (ANMS).
3. Bulletin Board System (BB).
4. Electronic Mail(EM).

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1. Notices to Airman (NOTAM).

2. Automated Notices to Mariners System (ANMS).

3. Bulletin Board System (BB).

4. Electronic Mail(EM).

5. Autodin Message.

6. World Wide Navigation Warning Radio Broadcast System (WWNWS).

7. Direct reception of constellation health from GPS satellites.

Table 3.1 presents a matrix indicating which transmission methods are compatible with each of the computational options.

TABLE 3.1

Transmission Method/Computational Means Compatibility

Transmit Method	Reported Directly	Precomputed and Put in a Book	Computed by a Microcomputer
NOTAMs	LIMITED	YES	YES
ANMS	LIMITED	YES	YES
BB	LIMITED	YES	YES
EM	LIMITED	YES	YES
WWNWS	NO	YES	YES
AUTODIN	LIMITED	YES	YES
GPS	NO	YES	YES

Utility: Next, the alternatives are evaluated in terms of utility. The the first three measures of utility are directly related to the chosen means of transmission and are summarized in Table 3.2.

Table 3.2

Transmission Methods Utility Measures

Transmit Method	Response Time	Users Reached	Reliability
NOTAM	20 to 30 min	Nearly all Aviation Users	High
ANMS	20 to 90 min	Nearly all Maritime Users	High
BB	15 min	Users with Access to Computer and Modem	Med-Low
EM	15 min	Sophisticated centers for further distribution	Med-Low
WWNWS	30 to 90 min	Nearly all ocean going vessels	High
Autodin	30 min to hrs	Locations with message centers	Med-High
GPS	10-20 min	Users with receivers designed to display constellation status	High

The last three measures of utility are directly related to the computational option selected and are estimated as summarized in Table 3.3.

Table 3.3

Computational Means Utility Measures

Computation Method	Accuracy	Ease of Use	Level of Detail
Reported Directly	High	High	Med
Precomputed Book	Med	Med	Low
Microcomputer	Med	Low	High

<u>Cost</u>. Cost is the next consideration in evaluating alternatives. Many of the costs involved in implementing a system are common to all alternatives and do not affect choices among alternatives and are thus not addressed in depth. Similarly, even though some specific costs are difficult to analyze, it may be easy to conceptualize comparisons between alternatives, and this approach is taken with some cost figures. Additionally, many alternatives involve sunk costs of systems that are required and in place for reasons other than GPS status reporting. These costs are considered only to the extent that a reporting system would require expansion or modification to existing or planned systems. Choosing whose costs to include is another challenge in trying to determine accurate cost estimates.

The approach taken here in evaluating alternatives is to consider those costs which would be incurred by the federal government. This is in keeping with Office Of Management and Budget directives, but not common to the way funding is

commonly analyzed by the Air Force. It is penny wise and dollar foolish to design a system that minimizes cost to AF Space Command or USAF if it requires unnecessarily large outlays by other federal agencies like DMA or DOT. It is also inappropriate and counter to Congressional mandate for DOD to absorb costs that can be passed along to civilian GPS users. Therefore, it is assumed that costs incurred by users outside the Defense Department would be paid by the user.

Training and Operations Instructions (OI) development costs fall into the category common to whichever alternative is selected. Although some slight variation in level of effort could conceivably exist among different alternatives, the variation is hard to predict and is assumed negligible. In all likelihood, status reporting OI development will be put under the umbrella of the GPS control segment OI contract or a generic Scientific and Technical Assistance contract. Satellite controller training should be incorporated into current training curriculum, while user training will be handled in conjunction with military rating or civilian licensing programs.

Computer costs represent a significant cost for any status reporting system alternative proposed in this paper. Even so, widely varying current practices for estimating and projecting computer costs made estimating these costs difficult. For off-the-shelf equipment the Data Pro Research

Corporation series of pricing literature seems to be the most common first-cut cost estimation tool. Current negotiated contracts, GSA schedules, and past contract costs are also used to varying degrees. For software development estimations, an accepted method is the COnstructive COst MOdel (COCOMO) as described by Boehm in Software Engineering Economics (Boehm, 1981:117-140). Table 3.4 summarizes the cost estimates for computer software and hardware made for the various alternatives, and a detailed discussion of how the costs were derived follows.

TABLE 3.4

Computer Costs of Alternatives

Alternative Computation Method	Software	Hardware
Direct Reporting	$128,000	$50,000
Precomputed Book/Disk	$59,000	$30,000
Microcomputer Based System	$92,000	$300,000

Software development costs were computed using COCOMO. The Intermediate COCOMO equation was used to calculate Man Months of programming time to complete the effort. The cost of a Man Month of programming is estimated at $9000 including overhead. This is representative of several government analyst and programmer schedules from major software vendors

plus a 20% inflation factor. Nominal values for development effort were assumed, and the effort was considered to be classed as moderately stringent "semi-detached". Boehm distinguishes between a familiar, flexible programming problem he calls organic; the rigorous, constrained effort he calls embedded; and an intermediary situation containing some elements of both which he calls semi-detached. The COCOMO estimating equation used here is as follows:

$$MM = 3.0(KDSI)^{1.12}$$

MM is Man Months and KDSI is thousands of delivered source instructions.

The software estimate is based on 4 KDSI for the direct reporting system, 2 KDSI for the precomputed option, and 3 KDSI for the microcomputer system. This represents approximately twice the number of lines of FORTRAN code required of several programs designed for internal use that compute the required information. Even though there are possible development savings by modifying these existing programs, it is assumed that a total rewrite using ADA would be accomplished to reduce software maintenance costs.

Different estimates are used in all three alternative approaches because each approach has a unique requirement in addition to the basic visibility, geometry calculation. The direct reporting system will require extensive cross-referencing of the computed database, so the software effort

will increase. For the precomputed option, some plotting and summary presentation will add to the basic program. The menu driven, "user friendly" requirement for execution and editing of the micro based system will require significant expansion of the basic code.

Hardware costs for the direct reporting system are essentially sunk costs with the availability of an IBM 3083 system and backup currently in place to support GPS. The cost above represents the estimate that a dedicated disk drive could be a requirement for the status reporting system.

The hardware cost associated with the precomputed option represents an estimate of time-share costs or purchase of a dedicated minicomputer to compute many combinations of possible outages. With an 18 SV constellation plus spares, there are 1,561 possible combinations of outages to cover the loss of any 1, 2, or 3 satellites at once that must be computed.

The microcomputer hardware estimate assumes that if a system is chosen that mandates the use of microcomputers to calculate outage periods some additional hardware will be required. The rationale is that some federal organizations will take the opportunity to justify purchase of a system solely to implement status reporting. A total of 150 such dedicated units are factored into the estimate at a nominal cost of $2000 based on the current Air Force microcomputer contract with Zenith Data Systems. No inflation factor is

used because the trend in hardware costs is level or declining and is expected to remain so in the near future.

Costs of communication links required to implement any alternative system are almost exclusively sunk costs. Funding of federal data networks, phone lines, and some electronic mail capability exists irrespective of GPS status reporting systems. Because of other mission requirements, the communications capabilities at the Satellite Operations Center are excellent. This capability should not be taxed in the foreseeable future by the infrequent use of some capability for status reporting. Since Autodin has no utility measures that exceed other alternative transmission means whose costs are also considered negligible, it is dropped from further consideration as a viable alternative.

There exists the option to provide GPS status on a commercial bulletin board system like CompuServe instead of the less sophisticated military run bulletin boards. No setup charges exist for establishing this type service, and charges are based on either the number of ports (lines) required or an on-line time charge.

One communication link which is not currently projected is a low cost receiver that can display constellation status from a direct reading of the GPS SV transmission. Research and development is being done in this area, both with receiver manufacturer funds and with some FAA funding. Estimating cost and quantity requirements of this equipment

and then establishing the portion of costs that are inherited from enhanced GPS operation is not possible in the short term. This capability does have long term potential merit, however, and may develop in time for consideration as a status reporting component. However, to fund such a development for the express purpose of status reporting violates a constraint of the problem definition for this paper.

Operations and Maintenance Costs associated with the different alternatives represent diverse requirements. In the direct reporting approach, the bulk of the cost should be associated with software and database maintenance. For the precomputed alternative, printing, distribution, and updating of supporting documents were considered to be the significant costs. The cost drivers for a dispersed microcomputer based system will also be software publication and revision costs.

Cost estimates of operations and maintenance are based on 1991 dollars using a 5 year time horizon and a discount rate to compute Net Present Value of 10%. This discount rate was determined using the current recommended method of using the treasury note rate with the maturation date closest to the time horizon of interest (Feldman, 1986:class notes).

Current practices indicate that O&M services would be contracted out, and that is the assumption used to calculate these costs. This assumption also allows for easier

calculations of true total costs. Table 3.5 summarizes O&M costs and is followed by a detailed explanation of how the figures were derived.

TABLE 3.5

Summary of O&M Cost Estimates
For Different Alternatives

Transmission Method	Computation Method	Total 5 Yr NPV
NOTAM/ANMS EM/Mil BB WWNWS	Direct Reporting	$450,000
NOTAM/ANMS EM/Mil BB WWNWS	Precomputed Book	$1,700,000
NOTAM/ANMS EM/Mil. BB WWNWS	Microcomputer Based	$500,000
Comm. BB	Direct Reporting	$950,000
Comm. BB	Microcomputer	$888,000

The direct reporting system O&M budget is estimated to require the equivalent of one full time computer analyst for software and database maintenance. This figure is assumed to be constant over the five year life of the status reporting system, and a yearly figure of 108,000 is used. This again is based on current representative market rates adjusted 20% for inflation. Total NPV O&M cost for this approach based on the assumptions above is $450,000 then year dollars.

Operations and maintenance costs for the precomputed

book system are determined by using price and quantity figures for a comparable FLIP document currently in print. The costs are based on the current National Oceanic and Atmospheric Administration price of $1.50 per copy of The Airport/Facility Directory for volume purchases (NOAA, 1985:12). A comparable figure can also be derived by using the Defense Mapping Agency printing cost, of $.75 for their IFR Supplement, United States, and factoring in 100% overhead costs. DMA produced approximately 110,000 supplements covering the US, Europe, and the Pacific in 1986. Republication schedules range from 13 times a year for the European Supplement to 2 times a year for the US VFR Supplement. A semiannual revision schedule is chosen for cost estimation using the following requirement rates:

1991	60,000 copies
1992	60,000 copies
1993	80.000 copies
1994	120,000 copies
1995	120,000 copies

The total net present value in then year dollars for this scenario is $1.7 million. If revision is required only once year, the total NPV is $850,000.

The major O&M costs for a microcomputer based computation system would seem to be in the publication and distribution of program disks. Reconfiguration of the SV constellation such as moving spares or adding backup SVs would not require a reissue of the software program. Therefore, it is assumed that fewer revisions would be

required. Also, backup copies could easily be made at subordinate levels, so the total distribution requirement would be small compared to the precomputed option. The equivalent of one full-time analyst and one administrative assistant for the first year and part-time support at 50% of that rate in follow-on years is the basis for this portion of O&M costs. A distribution of 10,000 copies at $3 a copy with four revisions, 2 in the first year and 1 in each of the following 2 years, is assumed. Total NPV O&M = $500,000.

If the microcomputer computation method is used with a bulletin board, program updates and distribution cost could be saved by loading the updates directly onto the bulletin board, reducing the O&M costs to $388,000. Commercial bulletin board rates are based on the CompuServe flat rate fee of $10,000 per month for a contribution to NPV of $500,000.

Conclusion

This chapter has explained the methodology used in this analysis and discussed the process of completing the first fours steps in the Systems Engineering approach. Utility and cost measures for different alternative components were developed at some length to complete the systems analysis step. The next chapter presents a proposed total system that strives to take advantage of best utility features of several options while controlling costs.

IV. Model GPS Status Reporting System

A model GPS status reporting system is developed in this chapter. This model is the result of a trade-off study of the system requirements, potential solutions, and costs. First, an overview of the design philosophy and major components of the system are introduced. This is followed by a detailed discussion of parameters selected and the requirements of the software to implement the system. Next, cost estimation is addressed, using the previous chapter costs as a basis. The chapter concludes with a brief explanation of how the system would work.

Overview

To the maximum extent practical, the proposed status reporting system uses the expertise, structure, and equipment expected to be in place in 1991. For example, weather circuits that currently carry NOTAM information are proposed in lieu of a dedicated GPS network. A user perspective is assumed when making decisions on how to present and index information. This prospective produces the corollary assumption that it is wiser to process the data automatically than to expect users to manipulate and calculate partially processed data. Also, for the same reason, the design uses procedures and products already familiar to users when possible. The rationale for this is to maximize user acceptance and minimize training time required to gain

proficiency in using the proposed system.

Use of automation to provide an efficient and effective status reporting system is viewed as critical because of the time and manpower constraints to produce the needed information. The proposed system would require computing capability (probably at speeds comparable to a 1986 mainframe computer) to calculate areas and times of degraded coverage whenever outages occur. Also required is software to perform these calculations and to provide formatting in a functionally oriented form. A two-part database would be established whenever a satellite vehicle (SV) problem occurred or the constellation was changed for any reason. The first part of the database would simply be the current operating constellation configuration. A second, more extensive database would contain outage times for various locations on earth.

Master Control Station (MCS) access to the Air Weather Networks (both military and civilian) is the next major component of the envisioned system. Plans call for such access at the Consolidated Satellite Operations Center (CSOC), but provisions would be required to automatically transmit the GPS data on the weather circuits. Additionally, electronic mail capability to the Defense Mapping Agency Hydrographic office and others would be required for disseminating constellation changes. Finally, a software package for use on microcomputers capable of taking the

operating satellite data and customizing parameters of the system for specific uses would be made available.

<u>Specifics of the Proposed Design</u>

<u>Mainframe Hardware</u>. Computational capability would be provided by the IBM mainframe computers that are part of the Master Control System. Primary and backup capability is available using the three IBM 3083 systems currently in place at the Satellite Operations Center. They should have the capability to directly port SV constellation information into the status reporting software.

<u>Mainframe Software</u>. Mainframe software would be required to generate a two-tier database. The first part of the database would contain constellation status, while the second part would contain locations and times of degraded coverage. A review of how satellite (SV) orbits are normally described is presented to provide an understanding of what information is required for the constellation status database.

Any satellite can be completely characterized by six pieces of information often called orbital elements. Below is a list of the orbital elements as summarized by Bate, Mueller & White, who use a vector-oriented explanation:

1. Semi Major Axis (a constant that defines the size of the orbit--radius of circular orbit--27000 KM for GPS)

2. Eccentricity (shape of the orbit--zero for the essentially circular orbits of GPS).

3. Argument of Perigee (where the SV reaches its closest point to earth--not an important parameter for circular orbits of GPS).

4. Longitude of the Ascending Node (the longitude where the SV crosses the extended equatorial plane of the earth from the southern to the northern hemisphere--spaced every 60 degrees for GPS).

5. Inclination (the angle between the extended equatorial plane the direction plane of SV travel--55 degrees for GPS).

6. Time of perigee passage (for circular GPS orbit measured as an angle from the extended equatorial plane for a snap shot in time called the epoch and referred to as the argument of latitude at epoch or the mean anomaly) (Bate, and others, 1971:58).

Constellation Status Database. The first segment of the status database would describe each satellite making up the current operational constellation in terms of orbital elements. Since the earth is not a perfect sphere, and there are slight variations in its magnetic field, as well as perturbations caused by the sun and moon, a circular orbit is an approximation. However, the assumption of circular orbits has a negligible effect on satellite visibility and geometry for the purposes of determining coverage (Isler, 1985:A-1).

The combination of these elements is normally referred to as the satellite or constellation ephemeris. An example of the most often discussed operational GPS ephemeris is presented in Table 4.1 as an illustration of how it would appear when queried for GPS status. Note that changes to a nominal published constellation ephemeris are flagged. This flag would be used by a user with special requirements for input into microcomputer software that allows customizing

expected coverage areas.

Table 4.1

Reference Orbit Parameters
Baseline Satellite Deployment

Satellite Number	Orbit Plane	Longitude of Ascending Node	Right Ascension of Ascending Node
1	1	0.18	30
2	1	240.60	30
3	1	300.12	30
4	2	260.80	90
5	2	320.14	90
6	2	20.20	90
7	3	340.16	150
8	3	40.22	150
9	3	100.28	150
10	4	60.24	210
11	4	120.30	210
12	4	180.00	210
13	5	140.32	270
14	5	200.20	270
15	5	80.26	270
16	6	220.40	330
17	6	280.10	330
18	6	160.34	330
Spares			
19	1	195.15	30
20	3	215.35	270
21	OUT OF SERVICE 1 JUL- 19 DEC 91		

NOTE: This ephemeris data is the same as that found in FLIP General Planning dated Sample Date and "Micro computer GPS Coverage Software" Ver 0.0 Except SV # 21 is out of service. (Parkinson & Gilbert, 1983:1181)

Degraded Coverage Database. By using coordinate transformations and the ephemeris data, the position of all satellites can be calculated with respect to any position on earth for any given time. The software to generate a more extensive database that identifies global coverage for a

given constellation represents the second major component of mainframe software. This is not an insignificant task even for a mainframe computer and will require some trade-offs to allow timely execution. One major trade-off is the number of points on the globe sampled to determine coverage.

The present model proposes selecting 100 points in the contiguous 48 states of the US (CONUS) and 400 additional points to cover the remainder of the world. Selection criteria for all points emphasizes geographic dispersal, major air and sea route coverage, and areas of high interest to DOD.

Sampling Point Selection. Before discussing the sampling approach recommended in this paper, a common current technique for selecting sampling points is reviewed. One common method of choosing points on the globe to sample for determining GPS degraded coverage is to uniformly increment by latitude and longitude. For highly detailed coverage, 2 degree increments are common. This method has useful applications in designing and testing satellite systems and provides good graphic data points. It is not, however, either oriented to user needs or efficient in providing useful coverage information.

People are generally more comfortable with identifying areas of interest by referencing landmarks than latitude and longitude coordinates. Therefore, it is recommended that sampling points, when practical, be easily recognized

landmarks, like major cities, instead of coordinates. In remote areas this will not always be possible, and longitude and latitude or less well-known landmarks will be required.

By careful selection, the number of sampling points can also be significantly reduced with little or no impact on the amount of useful information available. Time is a factor in producing degraded coverage information. It seems wasteful of time, computer capability, and telecommunications capacity to make extensive calculations for large areas of little navigation interest to general purpose users. Specifically, the South Pacific, Africa, and Central Asia could be adequately covered using fewer sampling points than an equal geographic area in CONUS or Europe.

Selecting sampling points by uniformly incrementing longitude and latitude every 2 degrees would require approximately 375 points for CONUS and 15,300 points for world-wide coverage. However, the 100 points proposed for CONUS provides essentially the same degraded coverage information with a slight loss of detail in some areas. The proposed system also allows for more detail at important points where extensive navigation demands can be expected and allows easier identification of those points.

Table 4.2 contains criteria used for selecting 100 proposed CONUS sampling points in the order they were applied. They are also recommended as guidelines for selecting remaining sampling locations around the world.

Some further definitions of several terms are necessary and are presented here. A major city is defined as a metropolitan area with a population of 1,000,000 using 1980 census figures. Geographically dispersed is defined as at least 60 nautical miles separation between area centers. For example, even though Newark, NJ is a major city, it is adjacent to New York City and so is not used. A metropolitan statistical area (MSA) is defined by an OMB directive, 30 Jun 1983 as revised through 30 June 1985 (Rand McNally, 1986:53). Generally, a MSA is a central city with a population of at least 50,000 and the surrounding suburbs. Military significance is defined as a location of a major US military installation.

Figure 3 is a plot of points selected in the CONUS using these criteria. The list of points are contained in Appendix B.

Table 4.2

Selection Criteria for
Sampling GPS Coverage

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1. Geographically dispersed major cities.

    a. major port, air center, rail and highway center

    b. major coastal port or boarder city

    c. air, rail, or highway center

2. Metropolitan statistical areas (MSAs) geographically dispersed from Major Cities.

    a. coastal MSAs

    b. border MSAs

    c. MSAs defining a major air route

    d. MSAs co-located with a major US military installation

3. Minor landmarks geographically dispersed from major cities/MSAs

    a. coastal towns with sea, air, rail, highway, or military significance

    b. boarder towns with sea, air, rail, highway, or military significance

    c. locations that boarder several states with air, rail, highway, or military significance

    d. towns with air, rail, highway or military significance

4. Cardinal latitude and longitude coordinates geographically dispersed from all the above

    a. sea and air significance

    b. sea or air significance

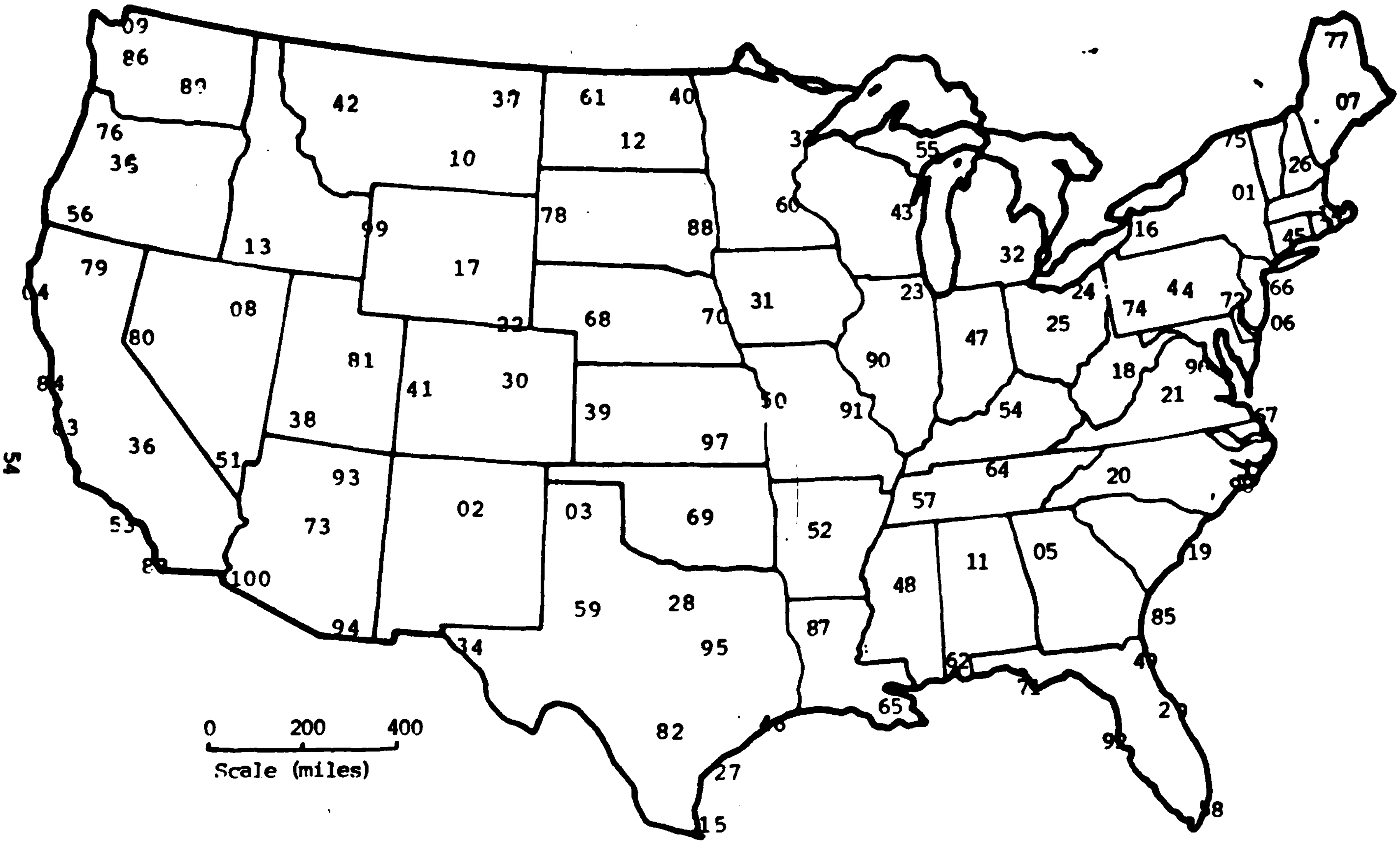

Figure 3. Map of Recommended US Sampling Points

One of the goals of the point selection was to provide detail at least as good as a random 2 degree grid for every major commerce center in the country. The measurement used to determine accomplishment of this goal was for each of the 150 largest metropolitan areas to be with 100 miles of a sample point. The 100 mile figure is the approximate worst case miss distance of any point using a random grid spaced at 2 degrees. This was easily accomplished with 50 sample points co-located with these centers, less than 10 percent more than 50 miles removed, and all points within the 100 mile criteria.

Another goal was to have all major military installations meet the 100 mile criteria. This was not achieved, as 7 of the 275 installations published by Rand McNally as major US military installations were more than 100 miles from a chosen point (Rand McNally, 1986:52-53). However, degraded coverage estimates for a limited sample of satellite outages provided accurate results by selecting nearby sampling points in every case tested. For example, Laughlin AFB in Del Rio Texas was an outlying installation, but San Antonio and El Paso samples covered the periods when Laughlin would not have good coverage.

Obviously, the detail of the proposed system is not uniform world-wide, as there is more detail available for the United States and less for remote areas of the globe. There are two reasons for this feature in addition to the arguments

of efficiency and ease of use made previously.

The first reason for this approach is preventing redundancy in status reporting systems within the US. If GPS is used for civil aviation and maritime navigation, the US government will most likely pay for the detailed status reporting system required. As mentioned in chapter three, the approach in calculating system costs here is to include costs to the US federal government as a whole. No attempt is made in this analysis to establish DOD and DOT shares of status reporting system cost.

A second reason that allows limiting the detail for areas outside the US is that all the information needed to calculate finer detail of coverage is available in the ephemeris information part of the database. Organizations that require specialized or detailed information would be free to generate and distribute it as needed.

Degraded Coverage Parameters. Table 4.3 contains the assumptions which are recommended for use in creating the degraded coverage database. The rationale for their selection follows.

Table 4.3

Degraded Coverage Parameters

1.	Nominal accuracy exceeding 100 meters horizontal (2D) error constitutes degraded coverage. A HDOP of 10 is a suitable estimation of this accuracy.
2.	A satellite is considered visible if it is at least five degrees above the local horizon.
3.	Satellite positions are sampled at 2 minute intervals to determine visibility and geometry.
4.	A maximum of 500 locations are used to generate world-wide coverage degradation.
5.	Degraded areas are reported for a period of 24 hours following any change to the constellation from its nominal configuration. Updates would be made in 24-hour increments, 12 hours prior to the expiration of the valid times for previous data, if required.

The first assumption above is based on the requirement of the FRP for future air navigation aids certified for non-precision approaches requiring 100 meter accuracy (FRP, 1984:II-19). The implementation of the accuracy assumption using an HDOP of less than 10 is based on developmental test results. This greatly reduces the number of calculations required to determine degraded coverage areas. Choosing an HDOP of 10 as the geometric equivalent of 100 meter accuracy, one has only to consider a constellation with less than 5 satellites in view as a potentially degraded area. This assumes nominal error budgets for factors other than satellite geometry.

The second assumption of using a 5 degree mask angle for

the 24 hour period, if the SV problem is expected to be long term, degraded coverage would occur at approximately the same times for the following days.

Database Access Requirements. A critical element of the resulting database is how it is indexed and cross-referenced for easy access. This is a direct result of the fact that there are many different users with different needs. A layered, menu approach to access the information by one of several key words is suggested. The MCS would transmit the database to Carswell AFB weather switch with addressees getting that portion of the database they request. The FAA, for instance, would likely want the entire North American database loaded directly into their central computer in Kansas City. This data should be retrievable by flight service or base operations personnel using one of several different cross-referencing options. Cross referencing examples are illustrated in Figures 4 and 5.

Figure 4 presents a sample of an initial screen display that would allow query by several means. The operator could either press the number to display the codes for each of the options or, if the code is already known, it could be entered directly. Figure 5 shows a sample follow-on screen that contains all degraded coverage for an area of interest. In this example, the state of Colorado was selected. The degraded coverage for the state would consist of all times that any of the displayed sample locations had a calculated

a baseline allows for system use in the vast majority of user scenarios. It also provides a realistic measurement of designed performance and does not penalize all users by imposing stricter criteria required for a very limited number of applications.

The recommendation that a two minute sampling interval be used is based on numerous computer runs to analyze the behavior of constellation geometry. Bad geometry can occur quickly and be resolved quickly as SVs cross planes or rise and fall from the observer's field of view. This short sampling interval assures detection of virtually all bad geometry. However, it also increases computations, so there is a direct trade-off between sampling interval, number of sampling points, and duration of reporting period.

Choosing to limit the number of sampling points to 500 is a direct result of the trade-off mentioned. See the previous section of this chapter for more detailed rationale for point selection.

The recommendation for a 24 hour reporting interval reflects the computational trade-off mentioned above and the requirement for providing advance planning information. It also considers the view that most SV problems should be resolved in that period of time. This allows for only one transmission in most cases, with the added advantage of providing a complete cycle of possible outage times for a specific constellation status. This means for planning past

outage time.

If a smaller area of interest (eg. Denver) was desired, it could be selected from either of the sample screens. From the screen in Figure 4, if the city number or VOR identifier were known, it could be entered, and degraded coverage times for Denver would be displayed. From the screen in Figure 5, the operator would enter the displayed number code for Denver to display the same data.

The sample screens are for illustration only, and in all likelihood a standardized format would be used to reduce the data flow requirements. For instance, "out of service" is typically abbreviated "OTS". Other abbreviations and formatting are also probable. The end result is that all the information shown in figure 5 would likely take up one or two lines on an 80 column display.

```
                         Sample Screen

              GPS DEGRADED COVERAGE USA DATABASE

Press 1 to Display City Codes or type Two Digit City ID

Press 2 to Display State Codes or Type State ID

Press 3 to Display VOR Codes or Type VOR ID

Press 4 to Display Stored Route or to Enter New  Route

Press 5 to Change Database or Exit
```

Figure 4. Sample Screen for Database Cross Referencing

```
                         Sample Screen

                     GPS DEGRADED COVERAGE

DATE:  0001-2359Z 23 Sep 86      AREA:  Colorado, USA

SATELLITE STATUS:  SV # 16 Out of Service

TIMES:  0200 to 0220Z, 1840 to 1910Z

SAMPLE LOCATIONS USED TO DETERMINE COVERAGE:
 2. Albuquer NM   22. Cheyanne WY   30. Denver CO
40. Goodland KS   42. Grand Jun Co

TOTAL DEGRADED COVERAGE TIME:  50 Min. in 2 Time Blocks

Press # to View Sample Times, or ESC to Return to Main Menu
```

Figure 5. Sampl Screen for Area Query of Database

Communications Requirements. As noted above, MCS access to military and civilian weather networks is the recommended means of dissemination to all aviation users. By 1991, US domestic military and civilian NOTAM systems will be combined and automated. Therefore, it is anticipated that all areas of coverage degradation as defined above for the United States and coastal waters could be stored for access in the FAA database. The FAA would be responsible for determining what information and in what format would be made available for international civilian NOTAMs. Military users overseas would get information through overseas military NOTAM channels via the Carswell AFB switch.

Electronic mail would be used to notify selected military operations and the DMA Hydrographic Office for dissemination into the ANMS. In all likelihood, only changes to the ephemeris data would be transmitted over some ANMS links while more detailed information would be available via other ANMS services.

WWNWS Example: "GPS SV #21 out of service 1DEC910900-2300Z"

It is anticipated that the eight Coast Guard districts responsible for local notices to mariners would access the central database for their areas of responsibility and retransmit appropriate information.

Microcomputer Software. Another software package capable of running on a microcomputer is required to

supplement the mainframe program described above. This program would allow any user to update a constellation ephemeris using just the first part of the central database. With this information, one could adjust assumed parameters to meet specific user requirements. The program would be designed to run on the most popular micro computers in use as typically configured (For example, IBM PC or compatible, Apple Macintosh, 256K minimum memory, 2 disk drives). Execution speeds of less than two minutes for a benchmark computation are desired. The program should be menu driven, allow for alternative default values to be permanently stored, and be tamper resistant.

Figures 6 through 11 contain a series of sample screens that illustrate some of the desired software features. Access to on-screen help, error tolerance, and the capability to skip over unneeded menus should be emphasized.

```
                         Sample Screen


               GPS COVERAGE DETERMINATION PROGRAM


    This program allows modification of the parameters
    used to calculate areas of degrade satellite coverage
    to meet specialized mission needs.


    Information on degraded GPS coverage to meet most
    requirements is available at a local base operations,
    Coast Guard office, or Flight Service Station.

    WARNING:  This program is for planning purposes.  Its use
    for making navigation decisions is subject to restrictions.
    -----------------------------------------------------------
                  Press Enter to Begin Program
```

Figure 6. Introductory Screen to Microcomputer Program

```
                         Sample Screen


                         GPS MAIN MENU


          1.  Satellite Menu

          2.  Parameter Menu

          3.  Help and Instructions

          4.  Determine Degraded Coverage for Baseline Satellite
              Constellation and Current Parameters

          5.  Store Parameters

      -------------------------------------------------------
      Arrow Keys to Move Through Menu, Enter to select choice
```

Figure 7. Main Menu Screen for Microcomputer Program

```
                         Sample Screen

                       GPS Satellite Menu

1.  Load baseline ephemeris and determine coverage

2.  Load updated ephemeris and determine coverage

3.  Load and edit baseline ephemeris data

4.  Load and edit updated ephemeris data

5.  Create new ephemeris data

---------------------------------------------------------
Type F1 for Help... ESC to return to Main Menu
```

Figure 8. Satellite Menu Screen for Microcomputer Program

```
                         Sample Screen

                       GPS Parameter Menu

                                    (current values)
1.  Location                         Den VOR
2.  Altitude                         0 Meters
3.  Date                             1 Jul 89
4.  Start Time                       0 Sec (0 Hrs)
5.  Stop Time                        86400 Sec (24 Hrs)
6.  Time Increment                   120 Sec (.08 Hrs)
7.  Mask Angle                       5 degrees
8.  Accuracy Threshold               100 Meters Horizontal

Type the corresponding number to edit a parameter or [illegible]
to determine coverage with set parameters
---------------------------------------------------------
Type F1 for Help... ESC to return to Main Menu
```

Figure 9. Parameter Menu Screen for Microcomputer Program

Sample Screen

GPS Constellation Status

SV#	STATUS	SV#	STATUS	SV#	STATUS	SV#	STATUS
1	GOOD	9	GOOD	17	GOOD	25	N/A
2	GOOD	10	GOOD	18	GOOD	26	N/A
3	GOOD	11	GOOD	19	GOOD	27	N/A
4	GOOD	12	GOOD	20	GOOD	28	N/A
5	GOOD	13	GOOD	21	GOOD	29	N/A
6	GOOD	14	GOOD	22	N/A	30	N/A
7	GOOD	15	GOOD	23	N/A	31	N/A
8	GOOD	16	BAD	24	N/A	32	N/A

Type the coresponding number to change satellite status
or type 0 to calculate coverage with the current status

Type F1 for Help... ESC to return to Main Menu

Figure 10. Constellation Status Screen for Microcomputer Program

Sample Screen

GPS Degraded Coverage for

1. Baseline ephemeris, 18/6/2 + 3 spares, created 1/01/89

2. Den Vor, 0, 0001 to 2359Z 1 Jul 89, 120, 5°, 20 3D.

3. SV #16 BAD

GPS Error is calculated to exceed the selected threshold

0900 to 0930Z

WARNING: This calculation is for planning purposes only and
its use in navigation decisions is subject to restrictions

Type F1 for Help... ESC to return to Main Menu

Figure 11. Degraded Coverage Output Screen for Microcomputer Program

For example, assume a GPS user received information that satellite #16 had been placed out of service for 24 hours. If one wanted to determine if Denver would experience 3 D degraded coverage in the next 24 hours it would be accomplished by:

1. Pressing 1 on the main menu to select the satellite menu.
2. Pressing 1 on the satellite menu to load baseline ephemeris data and determine coverage (this should call the parameter menu).
3. Pressing 8 on the parameter menu to change accuracy threshold to the desired value.
4. Pressing 0 to determine coverage (this should call the constellation status screen).
5. Pressing 16 to turn off satellite #16
6. Pressing 0 to calculate degraded coverage.

Degraded coverage information is presented in Figure 11. How this information would be used is dependent on the rules governing the specific type of navigation considered.

Cost

Controlling cost is a major objective of the proposed system. The assumptions used in cost estimations in chapter three are the basis of cost figures discussed here except as specifically noted. For convenience, the cost information contained in Tables 3.3 and 3.4 are reproduced in Table 4.4. The reader is referred to chapter three for further details of the cost estimations of specific components of the proposed system.

Table 4.4

Summary of Cost Estimates for Alternative Systems

Transmission Method	Computation Method	Computer Costs	Total 5 Yr NPV O&M
NOTAM/ANMS EM/Mil.BB WWNWS	Centrally Computed Direct Reporting	$178,000	$450,000
NOTAM/ANMS EM/Mil. BB WWNWS	Precomputed Book Reference	$89,000	$1,700,000
NOTAM/ANMS EM/Mil. BB WWNWS	Microcomputer Based	$392,000	$500,000
Comm. BB	Centrally Computed Direct Reporting	$178,000	$950,000
Comm. BB	Microcomputer Based	$392,000	$888,000

Table 4.5 summarizes the proposed system's cost. This is followed by a detailed explanation of the adjustments made from the originally determined costs for the elements comprising the prototype system.

Table 4.5

Proposed System Cost Estimate		
Software Development	$146,000	
Hardware	50,000	
Communications Links	0	(All inherited)
Status Reporting System		
Operations & Maintenance	685,000	
Total	$881,000	

Computer costs connected with the microcomputer option are adjusted in this proposed system. First, the hardware cost of purchasing microcomputers is eliminated. Since adequate information for most users is available in the basic system, it is likely that users requiring customizing input parameters would already have access to a suitable microcomputer for mission planning. Second, the cost used for microcomputer software development is $18,500. This represents 20% of the cost to develop the microcomputer software when considered as a primary alternative. This is based on the assessment that 80% of the software development for the mirco system would be converted directly from the primary, direct reporting system at little or no cost.

The O&M cost estimate for the microcomputer segment of the system is also reduced from $500,000 to $235,000. This assumes that the O&M contract would be a single contract and that some economies would be realized in terms of personnel productivity. A part time analyst costing $58,000 a year is used as the basis for the microcomputer contribution to personnel O&M costs. It also is based on a requirement to publish 1000 copies of the micro software package for government use, instead of the 10,000 copy estimate for a stand-alone micro based alternative.

How the System Would Work

To illustrate how the proposed system would operate,

a brief description of anticipated MCS activities is explored. This is followed by a discussion of several different user scenarios. The section concludes with an outline of potential problems that might be anticipated in the operation of the system.

Master Control Station Activities. The first step in implementing the status reporting system is for some responsible individual at the MCS, possibly the senior controller, to determine that a SV will be lost for navigation purposes. Additionally, the anticipated duration of the loss must be longer that the period required to disseminate the information. Perhaps 30 minutes is an appropriate target time, so if the outage is expected to exceed 30 minutes, the status reporting program is called and run.

Prior to the transmission of the results, some verification of at least the ephemeris data would be made. The change would be immediately transmitted and also sent via electronic mail to DMA. When the new areas of degraded coverage are calculated, they would also be transmitted as described above.

Cross Country Flight Scenario. A pilot checking the weather and NOTAMs for a planned cross country flight would have GPS flagged if there were any changes to the standard constellation. The pilot is using GPS for a navigation mission, and therefore would request the GPS flag to be

keyed. First, he would get the changes to the standard constellation ephemeris. When his normal NOTAMs and weather are displayed, any areas of degraded GPS coverage 50 nautical miles either side of his intended route of flight and their times would be presented. Depending on the backup equipment in the plane, the pilot would most likely just make a mental note to expect a GPS warning during the segment of flight flagged. Upon arrival at the destination terminal area, the pilot would update current landing conditions at which time GPS status changes that occurred while enroute would be briefed.

Tactical Training Scenario. The next pilot is planning a low level training route using terrain-following navigation, followed by a simulated bombing run. He will apply the changes to the standard constellation, to his micro computer program by turning "off" the SV that is unusable. He then runs the program with a mask angle of 15 degrees for his 4 low level check points. He will then need to change the accuracy threshold to 10 meters three dimensional position for the bombing range since this will be a GPS aided and scored bomb run. This whole process would take only 5 to 10 minutes.

Submarine Position Update Scenario. A submarine relying on GPS for fix update would get a GPS status via coded message from his appropriate controlling agency in conjunction with normal/emergency message traffic. It would

be the controlling agency's responsibility to interpret degraded coverage areas for specific submarine locations and required accuracies.

Potential Problems. Potential problems exist with this proposed system. Availability of computer hardware and software on an as-needed basis is difficult to rely on. This is a two edged sword in that if you overutilize computer time or storage due to numerous changes in the constellation, it will be frowned upon as costly. Conversely, if the system operates as designed, there will be few instances when status reporting procedures are implemented, and the requirement for computer capability will be questioned. There is also a tendency for information systems requirements to proliferate as desirable new features are identified.

A similar situation exists with communications links: if used too much, response time is degraded, and if used too little they are eliminated. Obtaining priority maintenance is also a problem in such a climate.

Finally, distributing, controlling, and updating microcomputer based software is not a mature process in the DOD. User training, standardization, and software control are all challenges to be met if the micro software system is to run efficiently. There are also legal questions that might develop over where responsibilities of various parties begin and end.

Conclusion

No system will satisfy everyone, but an automated system that takes advantage of flexibility and emphasizes end-user friendliness can provide adequate service to the vast majority of interested parties. The GPS user with sophisticated navigation equipment will likely have the resources to extract any degree of accuracy desired from the ephemeris data provided in this proposed status reporting system. The user of less costly equipment is likely to be amazed at the accuracy and reliability of the GPS concept.

This chapter has proposed a system that considers the trade-offs identified in the systems analysis step. Many of the components of the alternatives are included in this system because they all offer advantages in at least one area of utility. Chapter five tests the proposed model using a questionnaire that solicits potential users' views on several key assumptions of the model.

V. SURVEY ANALYSIS

In this chapter,key aspects of the proposed model developed in the previous chapter are analyzed. This is done by discussing the results of a survey of military aviators who are potential users of GPS navigation capability. First, there is a description of how the survey was designed and conducted. This is followed by an hypothesis testing approach to presenting the results of the survey [illegible]. Finally, possible changes to the model based [illegible] inputs are discussed.

Survey Development and Administration

The purpose of developing [illegible] assumptions used in the proposed [illegible] modeled in the previous chapter [illegible] conducting the survey and [illegible] in Appendix A. In designing [illegible] made to be concise and [illegible] terminology. To facilitate [illegible] minutes to complete the [illegible] established. An open-ended [illegible] additional comments was also [illegible].

The survey was administered [illegible] navigators because they represent [illegible] many of the demands for any [illegible] were 102 questionnaires completed [illegible]

considered an adequate sample size to analyze the attitudes and opinions of interest. Responses were received from operational fighter and transport units, test wing personnel, and officers currently serving in rated supplement assignments. Due to limited time and financial resources, all persons participating in the survey were assigned to Wright Patterson AFB, OH in a variety of capacities.

About 50% of the questionnaires were administered in small groups where question intent was, on occasion, amplified beyond the specific wording contained in the questionnaire. The other half of the completed surveys were from individuals without an opportunity for clarification and were returned by mail. Surprisingly, 70% of the 75 questionnaires completed at individual convenience were actually returned, even though no formal method was developed to track individual surveys.

The questionnaire contains a brief explanation of its purpose in an introductory paragraph followed by 11 multiple choice questions that can be grouped into three segments. The first group of questions are background in nature. The second group deals with the issues of accuracy and three [illegible] requirements. The third group of questions [illegible] preferences exist for a hard copy based system [illegible] system. The last question is open-ended, [illegible]

Analysis of Survey Results

Three hypotheses are presented and discussed on the basis of the survey data. Observations are made throughout which are inspired by subsets of the data but which are not derived from statistical analysis. These observations are meant to provide perspective. Consensus (acceptability) is defined here as a minimum of 2/3 favoring a specific position. This figure was chosen because it represents the measure of one standard deviation for a normal distribution, and is more conservative than a simple majority.

The aviation experience level of the respondents is likely higher than the average military aviator since more than 90% indicate more than 1000 hours primary crew time. Also, even though an effort was made to solicit a wide range of aircraft type experiences, a lower than desired number of respondents indicated bomber and helicopter type aircraft experience. Despite these two characteristics, the assumption of randomness is used in analyzing the data for the purpose at hand: GPS status reporting.

Hypothesis #1. A reporting system that defines degraded coverage as any time that error exceeds 100 meters (328 feet) horizontal accuracy is acceptable.

Results. Survey question #5 addressed this issue. The results are presented in Table 5.1.

Table 5.1

Survey Results for GPS Degraded Coverage when Error Exceeds 100 Meters Horizontal

Response	# Responding	%
Too Restrictive	4	4%
About Right	84	83%
Not Restrictive Enough	14	13%
Total	102	100%

Finding. A student T test derived 90% confidence interval for "About Right" is 76% to 88%. Therefore, it is reasonable to not reject the assumption that 100 meter accuracy is acceptable.

Discussion. Most respondents indicated that 100 meters horizontal error was a suitable criteria for considering GPS coverage degraded. This is a compromise that allows use of the system for most applications, even during periods that exceed strict design specifications. The consequences of this result are that both computational demands and size of the database recommended in the proposed model are manageable at reasonable costs.

Of the 9 respondents indicating bomber type aircraft experience, 5 indicated that 100 meters was not restrictive enough. Although this sample size is not large enough to apply statistical techniques, the results strongly indicate that there is a perception in the bomber community that

stricter accuracy criteria is appropriate. One possible explanation for this result is that GPS is being touted as a bombing aid, and in this specialized use more accuracy is desired.

A consensus for accuracy in the range of 100 meters is indicated by the results of the survey. However, some capability to determine degraded coverage using much stricter criteria seems desirable to a minority of potential users. The system proposed herein provides this capability through microcomputer software combined with satellite (SV) constellation status information.

Hypothesis #2. Three dimensional accuracy for navigation use is not an important requirement of a reporting system.

Results. The results of survey question #6 addressing views on reporting degraded coverage in terms of 3 dimensional (3 D) accuracy are contained in Table 5.2.

Table 5.2

Reporting Preference

Response	# Responding	%
A must requirement	24	24%
Should be included	30	29%
Not a major concern	27	27%
Little reason to include	15	15%
Not a requirement	5	5%
Total	101	100%

Note: One respondent did not answer this question.

Finding. A student T test derived 90% confidence interval for either of the first 2 choices is 48% to 64%. Therefore, it is reasonable to reject the hypothesis that 3 D is not important.

Discussion. The survey results indicate that three dimensional accuracy is in fact a desirable feature of a status reporting system. With 53% of the respondents indicating that 3 D information "must" or "should be" included as part of a reporting system, the parameters in the baseline system may not be acceptable.

In the open-ended question several examples were given of navigation missions where the aid of GPS altitude information to crosscheck altimeter information would be beneficial. These examples generally related to remote area operations where reliable, current local altimeter settings are sometimes not available. Even though these applications represent only a small portion of air operations, their military importance may warrant further reporting system stratification. This could be done by including both 2 D and 3 D standard accuracy criteria. However, this would increase the computational requirements and database size required and add another set of data to be communicated and displayed.

Another possible solution is to establish one three dimensional accuracy threshold for reporting all degraded coverage. This would report an area degraded any time the 3 D expected error exceeded some nominal value, possibly 100

meters spherical error. The problem with this approach is that outage areas would be identified that are still usable for many applications. An example here may help to illustrate this point. Consider a full 18 SV constellation with three active spares and each SV singly removed from the constellation. That is, SV #1 is removed, then SV #1 is replaced and SV #2 is removed, etc. etc.. Table 5.3 summarizes the likelihood that an outage would occur, the total number of outages for a 24 hour period, and the average time duration of each outage.

Table 5.3

Comparison of 3 D and 2 D Degraded Coverage

Location	Degraded Coverage (Probability 3D/ Probability 2D)	Number of Occurrences (3D/2D)	Average Duration (3D/2D)
New York City	.57/.14	20/5	14/8 (min)
Denver	.57/.33	14/7	23/8 (min)
Miami	.38/.04	14/2	15/10 (min)

(Calculated using ZPDOPG program)

It is also possible that the microcomputer based supplement to the basic system would be an acceptable method of providing 3 D coverage information. This was not specifically addressed in the questionnaire, but the respondents rated acceptability of microcomputers as part of the system quite high.

Hypothesis #3. There is a clear preference for an automated system that provides degraded coverage areas directly over a hardcopy based system that requires referencing a book.

Results. The survey questioned views on a book reference system and an automated database direct reporting system separately. The reason for doing this was to independently get an indication of acceptability of each option. Figure 12 contains a graph of responses to the two questions (#7 & #10) that address the comparison between a basic precomputed book reference system and a basic automated system. Figure 13 plots responses to the basic book reference system and those of follow-up questions (#8 & #9) explaining some of the expected features of the system. Figure 14 graphs the responses for views on the basic automated system and a follow-up question (#11) on a microcomputer customizing feature. The respondents were not asked to indicate a preference between the two types of systems directly, which would be useful in a more detailed survey.

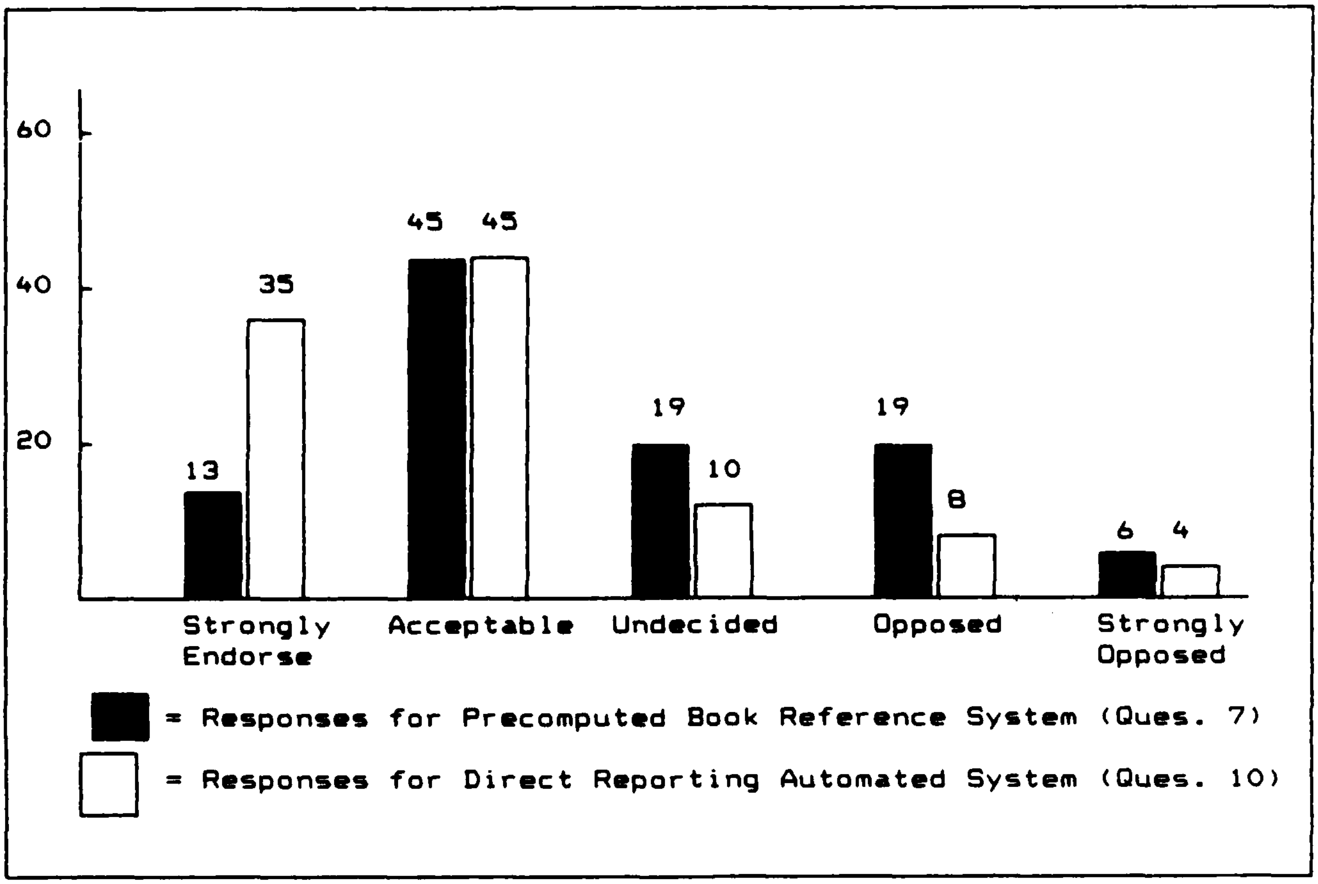

Figure 12.

Survey Results for Basic Book Reference and Automated Systems

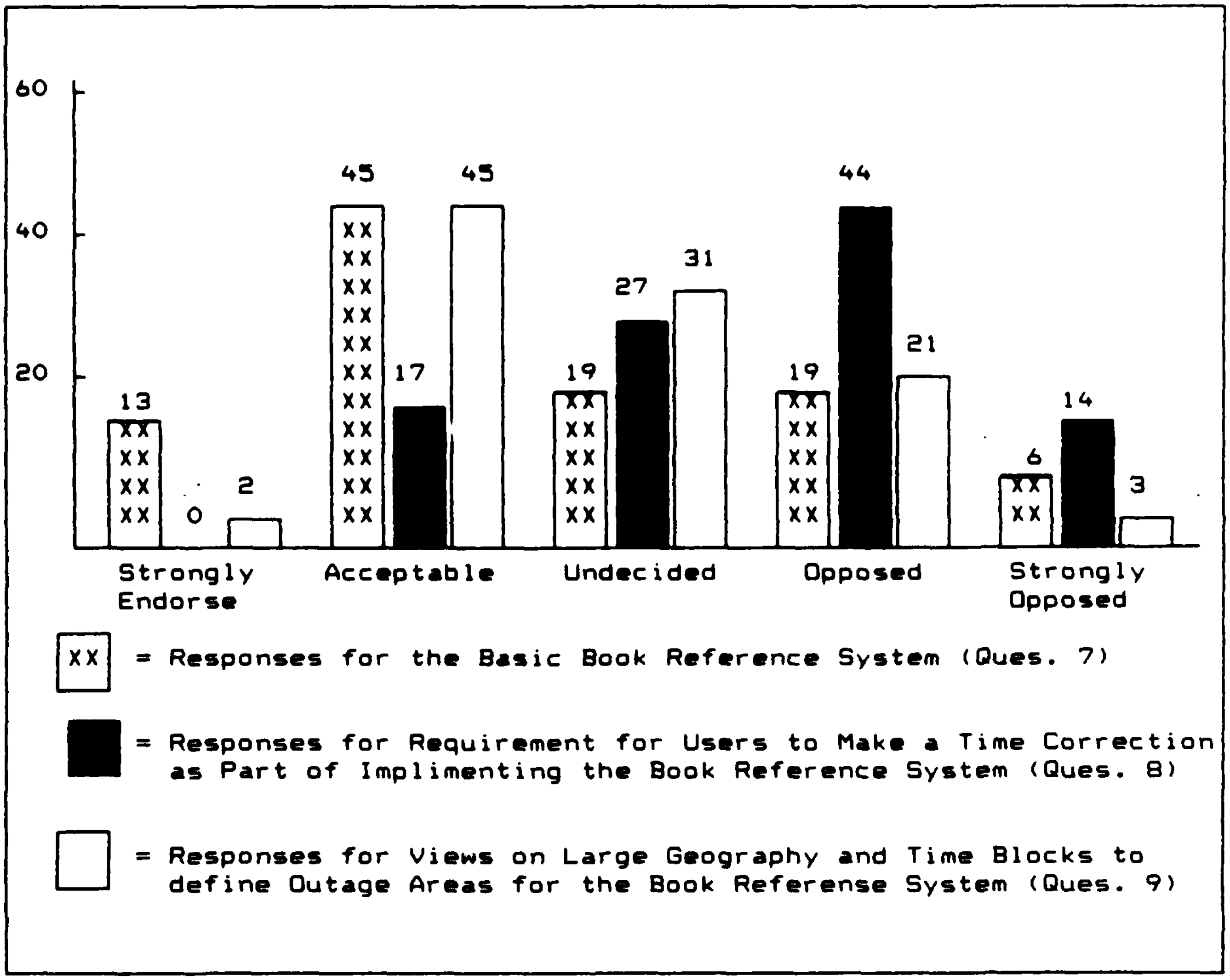

Figure 13.

Survey Results for Precomputed Book Reference System and Follow-up Questions

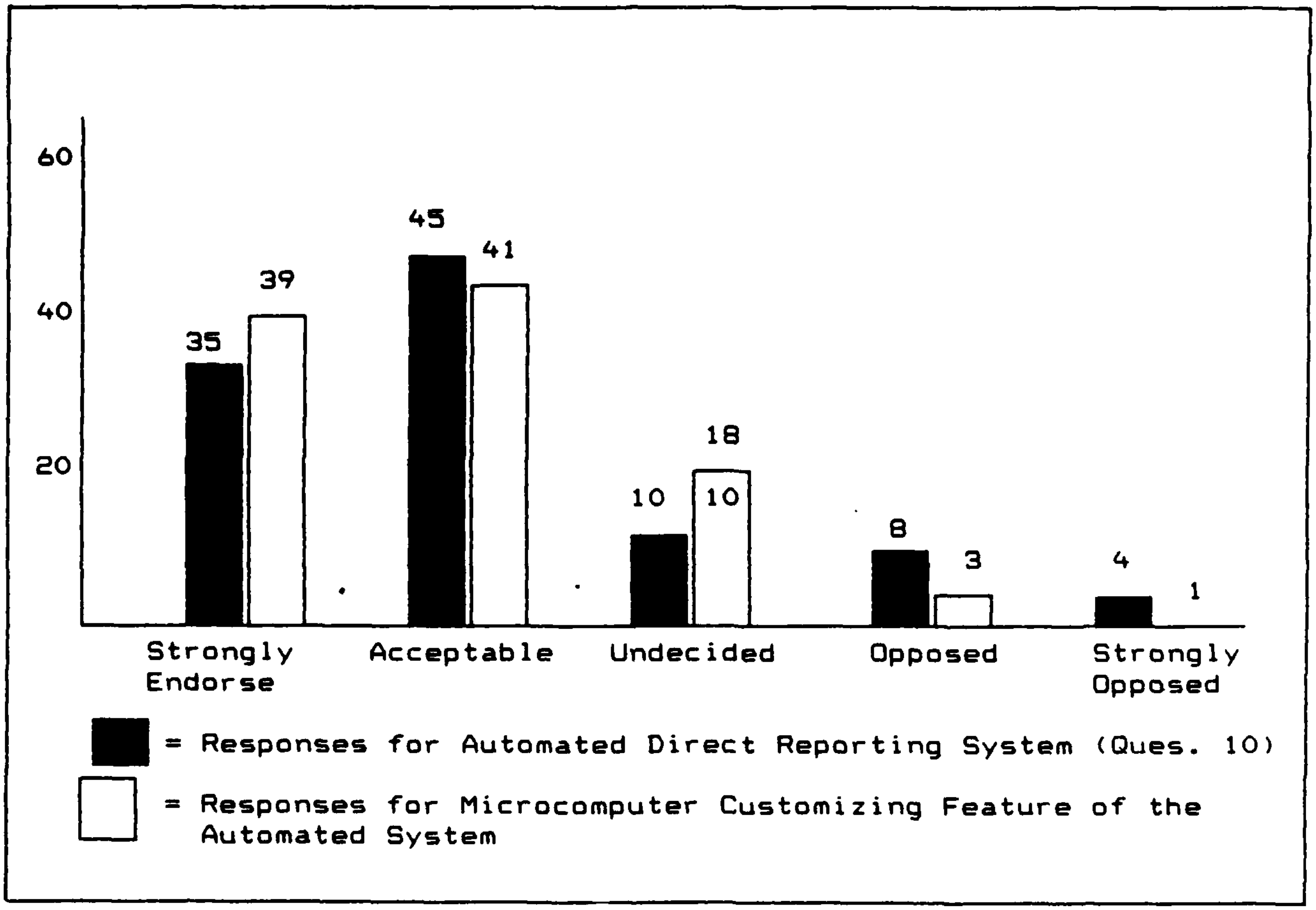

Figure 14.

Survey Results for Basic Automated System and Microcomputer Based Customization Feature

Finding. By any measure, the preference for the automated seems to be established. Individual and aggregate positive responses favor the automated system, and individual and aggregate negative responses also favor the automated system. Therefore, there is no reason to reject the hypothesis that the automated system is preferred.

Discussion. The survey indicates that most respondents find either of the basic systems fairly acceptable. A substantial negative response was indicated only when the details were given of how a book reference system would work with the current orbit characteristics of GPS. Requiring a time conversion calculation or look-up table was not well received at all. A fairly course level of geographic and temporal detail was, however, not so objectionable. These inputs should be considered by decision makers evaluating the the merits of any proposed status reporting system because user acceptance is a major element of any such system.

Another finding this writer considers important was the overwhelming endorsement of a microcomputer component of the automated system. Eighty respondents endorsed the microcomputer system component. Computer literacy, and confidence in the capability to effectively employ microcomputers as tools is clearly indicated. This is almost certainly the result of a general pervasiveness of interacting directly with computers at both school and work

for many of the respondents. Since, however, the survey reached a limited sample of potential users, some broader sample is probably appropriate to more precisely measure this attitude. Conversely, increased personal interactions with computers is a trend likely to continue. Acceptance of computers may even be expected to improve further by the time a system is implemented in 199[illegible] and beyond.

<u>Other Comments on Survey Results</u>. More than [illegible] survey respondents provided additional comments [illegible] question #12. Three themes were repeatedly expressed [illegible] most frequent and emphatic input was the idea of [illegible] in any system that is selected. However, defining [illegible] in universally accepted terms is often diff[illegible] addition, simplicity is usually in dire[illegible] an increase in a system's requirements [illegible] flexibility.

Another idea expressed severa[illegible] equipment should be capable of [illegible] areas of degraded coverage based [illegible] information. However, this added [illegible] designed into receivers is n[illegible] balanced with requirements and [illegible] feedback on the GPS navigation [illegible] presently designed user equipme[illegible] and does not project future [illegible] constellation. Finally, [illegible]

a major problem for Air Force user equipment, there is little interest in adding additional requirements to receivers until some operational experience is gained.

Several other comments suggested a multi-criteria reporting system. A system that differentiates between full [illegible] capability, and no capability was suggested. Terms such as "good", "marginal", and [illegible] were suggested to identify these respective [illegible] "green", "yellow", or "red" nomenclature might [illegible] Once again, this [illegible] flexibility at the cost of complexity.

[illegible] Based on Survey Results

[illegible] the proposed status reporting system are [illegible] the [illegible] survey results. This [illegible] based heavily on the input to keep the [illegible] It also represents the fact that by use [illegible] computer component of the system, all [illegible] are available. The reliance on a [illegible] customized status information seems [illegible] the strong positive response to use of [illegible] identified in the survey.

[illegible]

[illegible] has explained the purpose, mechanics, and [illegible] conducted to test several of the key [illegible] in designing a prototype status reporting

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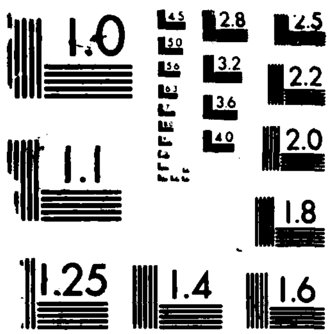

MICROCOPY RESOLUTION TEST CHART

system. Even with the survey's limited scope and depth, several assumptions were validated while others were called into question. Continued user input is strongly recommended to refine the concepts presented in the prototype system and to test other assumptions required to field a system. In the next chapter, the conclusions of the research effort are summarized, and areas and directions for further work are identified.

VI. CONCLUSION

This chapter recaps the problem addressed in this research effort and its findings. It also discusses some of the specific related areas that appear to warrant further study.

Plans for implementing GPS navigation continue as satellite launch problems have delayed initial operational capability into the early 1990s. The Department of Transportation's (DOT) Federal Aviation Administration and Coast Guard are taking a "wait and see" attitude toward GPS. This approach seems reasonable considering other priorities, budget constraints, and risk assessment of GPS civilian applications potential. Driven primarily by constituency pressures, LORAN-C is a proven short term GPS alternative for many civilian applications that is absorbing considerable DOT resources.

Meanwhile, the Department of Defense (DOD) and Air Force Space Command are exploring ways to provide system status information to the wide range of expected users. This research effort focuses on providing advanced planning information to the peacetime navigation user. It does so by proposing an automated status reporting system that uses much of the infrastructure already in place to support current navigation systems and requirements. Many of the components of the proposed system could also have broader application to GPS operational capabilities planning but are beyond the

scope of this paper.

GPS poses unique status reporting challenges because the number of orbiting satellites visible and their geometry are continually changing with respect to users. The problem is further complicated by the wide variety of users and applications which GPS is designed to support and their global dispersion.

Key Elements of Proposed Status Reporting System

Table 6.1 outlines the recommendations for a status reporting system as determined in this paper. Figure 15 provides a schematic of major agencies involved and information flow.

Table 6.1

Summary of Proposed Status Reporting System
Developed in this Research Effort

Key System Elements	Subordinate System Features
Centralized computation of degraded coverage areas.	Degraded coverage is defined as horizontal error greater than 100 meters.
	Sample locations for determining outages are major landmarks.
Satellite constellation configuration and degraded coverage areas are transmitted.	Some addressees will receive all information
	Some addressees will receive constellation status and a part of outage area information.
	Some addressees will receive only constellation status.
Electronic mail and Notices to Airmen systems are used by Master Control Station to initiate status changes.	Retransmission of parts of the data by electronic mail and radio broadcast are anticipated.
	Posting of data on electronic bulletin boards is a possibility.
Microcomputer software capable of determining outage areas using parameters different than the baseline system is required.	Variable parameters would include position, time, mask angle, and accuracy thresholds.
	Software would run on a range of commercially available microcomputers
	Time for computing a degraded coverage for a nominal situation would be less than 10 minutes

Areas For Further Study

The quest for suitable status reporting for a system as large and diverse as GPS is a dynamic process. As space, control, and user segments of the system evolve, so will the requirements of a status reporting system. This paper provides only limited detail on one solution. Further refinements of the actual workings of each element are necessary to implement the recommended solution. Specifically, four areas that this writer considers needing further work are as follows:

1. Developing computer code to prototype the proposed system.
2. Refining sample point selection criteria.
3. Cost estimation.
4. Expanded user input.

Prototype Software Development. There are several computer programs designed for internal company and organizational development use that compute satellite coverage areas. Aerospace Corporation of El Segunda, CA has developed programs called EGAD and COVERIT that could potentially be modified to develop a prototype capability. AF Space Command/XPS possesses ZPDOPG, a program designed to run on an IBM PC. It was used and modified in this research to consider various problems in developing the proposed status reporting system. Additionally, companies developing GPS user equipment have similar software packages.

Generally, this software has not been designed to optimize run-time for the specific application of computing degraded coverage. Documentation and output format are also not user oriented. Work on these areas and possibly translating the code into a more portable language like ADA would be beneficial.

<u>Sample Point Selection</u>. The approach for selecting sampling locations for calculating and reporting degraded coverage is an area that lends itself to further study. World-wide point selection could be attempted and more quantitative measurement criteria could be explored. Also, trade-offs for selecting additional points and the costs and benefits of more detail could be explored. Operations research networking techniques may be employed for selection and evaluation of chosen points.

<u>Cost Estimation Enhancements</u>. Cost estimation techniques used in this research are not very sophisticated, and additional work in this area would allow more precise cost/benefit analysis. Initial training and operations support documents costs were not quantified, nor were the status reporting system share of communications links costs. Further work in estimating the absolute costs in these areas would be worthwhile. Computer cost estimates are also imprecise.

The COCOMO model used to estimate software development costs has enhancements for providing better cost estimations

base on a wide range of variables not considered in this analysis. As software needs are more fully defined, it should be possible to better estimate their costs. There may also be more sophisticated methods for estimating computer hardware costs in the future that might be applied to this problem. Cost assumptions for operating and maintaining the various alternative systems may also warrant further evaluation.

Historically, software maintenance has been a major logistical expense of the US Air Force. Initiatives to improve this situation, like the requirement to program in approved languages, are ongoing. Some standardization assumptions were made in this research, but this is a dynamic area where cost estimation needs frequent refinement

Charges for military use of telecommunications networks also are subject to change and could invalidate some cost assumptions. Currently, the Defense Communications Agency budgets for operations of DOD networks. A change to a customer charge system would require a more detailed estimate of database size and transmission frequency to realistically estimate costs. Additionally, identifying trends in communications costs and projecting them into the future may be possible. However, this is a rapidly changing technology which makes this task difficult.

Improved User Feedback. The survey conducted as part of this research could be expanded to better test user attitudes regarding a status reporting system. The depth of the questionnaire could be increased, and the background information could be restructured to allow for more correlative measurements. A larger and broader survey sample would also be beneficial.

Table 6.2 contains several recommended questionnaire modifications and the rationale associated with each recommendation.

Table 6.2

Recommended Changes to Survey Questionnaire

Change	Rationale
Expanded introductory remarks explaining survey purpose and GPS system operation.	Several respondents made comments indicating this would be beneficial.
More background information; to include age, education level, and actual type aircraft flown.	Better correlation potential for attitudes about status reporting questions.
Different breakout of flying experience. Request total flying time or years of experience for non-aviation users.	More information to perform analysis and judge the validity of the sample.
Ask for direct comparison between alternate systems, displays, or outputs.	Allows for stronger evaluations of preferences.
Include sample screen displays of input and output formats.	Provides a tool for refining design of the system.

A broader base of potential GPS users is also desirable. As a starting point, more bomber, helicopter, and naval aviators are recommended. Surface ship and submarine user inputs are also needed. Civil airline and general aviation users should also be consulted. They not only may have slightly different requirements that may be easily incorporated into the design stage, they also have significant political influence in obtaining funds for implementing a system. A more generalized survey wording might be required to account for the wider range of experience of these different groups.

Other elements with substantial interest in GPS status reporting are army surface users. However, GPS represents a substantial departure from current operations for envisioned army applications of patrol navigation, artillery sighting, and armor maneuvers. In all likelihood, a different survey would be required to get substantive input from these forces.

Conclusion

This chapter has summarized the research effort described in this paper. The GPS status reporting system recommended here is an automated system consisting of a two-tier database that directly transmits both satellite constellation status and areas of degraded coverage. It also includes microcomputer software capable of customizing degraded coverage predictions based on differing parameters.

The chapter also identifies four areas where, in the

author's view, further research could be focused. The first area is actually developing computer code to implement the proposed system. Also, the sample point selection process could be further evaluated. The third area is cost estimation. More sophisticated cost estimation tools are available than were applied in this analysis. The final area identified is improving user feedback in designing a status reporting system. Changes to the survey questionnaire used in this research are suggested along with recommendations on how to improve the survey sample.

GPS represents a significant investment for the US Department of Defense. One requirement for realizing the considerable potential benefits of this system is an effective status reporting system. Hopefully, some of the ideas expressed in this paper will contribute to successful implementation of such a status reporting system.

Appendix A

NAVSTAR GLOBAL POSITIONING SYSTEM

Navigation User Status Reporting Questionnaire

GPS is a satellite based navigation aid that the Department of Defense plans to make its primary radio navigation system. It will replace TACAN, VOR, LORAN, OMEGA, and other navigation systems on military aircraft. This questionnaire is aimed at getting opinions on how best to report degraded coverage.

1. Flying experience (total time as a primary flight crew member)
    1. 0-200 hrs
    2. 200-500 hrs
    3. 500-1000 hrs
    4. 1000-5000 hrs
    5. More than 5000 hrs

2. Type Aircraft with more than 300 hours (if you have less than 300 total hours mark the type aircraft that you have the most time in).
    1. Fighter
    2. Bomber
    3. Transport
    4. Trainer/Other
    5. Helicopter
    6. More than one of the above selected

3. If you have a civilian pilot rating please list the highest rating and the approximate number of total pilot in command time you have in civilian aircraft__________________.

4. Prior to this questionnaire were you aware of the GPS concept?
    1. Intimately Familiar with the program
    2. Relatively Familiar
    3. Familiar
    4. Vaguely Familiar
    5. Completely Unaware

5. One proposed reporting system for GPS would consider any area that will not be provided with $\pm$ 100 meter (328 feet) horizontal accuracy as an area of degraded coverage. As a point of reference this is the accuracy required for non-precision VOR and TACAN approaches.

1. This accuracy is too restrictive, ____________ is what I think should be used.
2. This accuracy seems about right.
3. This accuracy is not restrictive enough, ____________ is what I think should be used.

6. With GPS equipment, a <u>three</u> <u>dimensional</u> <u>fix</u> in space is available. This adds altitude to horizontal positioning. Which response best expresses your view about reporting degraded navigation in terms of three dimensional accuracy?

1. Any system <u>must</u> report in terms of three dimensional accuracy.
2. Some information should be made available to calculate three dimensional accuracy.
3. Three dimensional information might be nice but not of a major concern to me.
4. I see little reason for reporting degraded coverage in terms of three dimensional accuracy
5. Establishing degraded coverage in terms of three dimensional accuracy is not necessary.

7. One proposed reporting system would publish a NOTAM stating only which satellite is out of service and refer the pilot to a FLIP type book to determine if he is affected.

1. I strongly endorse this concept.
2. I find this fairly acceptable.
3. I am undecided as to my opinion of this concept.
4. I don't think I like this idea very much.
5. I strongly oppose this concept.

8. (Ref. #7) If one were required to correct outage times by subtracting four minutes per day from a reference day how then would you view the proposed system?

1. I strongly endorse this concept.
2. I find this fairly acceptable.
3. I am undecided as to my opinion of this concept.
4. I don't think I like this idea very much.
5. I strongly oppose this concept.

9. (Ref #7) If size constraints on the FLIP book allowed for differentiation of only large geographic regions (perhaps eastern US) and large time blocks (perhaps 3 hours), how then would you view this system?

1. I strongly endorse this concept
2. I find this fairly acceptable
3. I am undecided as to my opinion of this concept
4. I don't think I like this idea very much
5. I strongly oppose this concept

10. Another proposed system would establish a database queried via base operations/FAA flight service computer terminals much like civilian NOTAMs are today. This system will be cross-referenced to allow outage information using latitude/longitude, area (state or country), VORTAC identifiers, or major air routes.

1. I strongly endorse this concept.
2. I find this fairly acceptable.
3. I am undecided as to my opinion of this concept.
4. I don't think I like this idea very much.
5. I strongly oppose this concept.

11. (Ref#10) The database could also include information on individual *satellites*. This additional data could be used with a microcomputer program to customize coverage for special mission requirements. How then would you view this system.

1. I strongly endorse this concept.
2. I find this fairly acceptable.
3. I am undecided as to my opinion of this concept.
4. I don't think I like this idea very much.
5. I strongly oppose this concept.

12. Please make any other comments you think might be useful to someone trying to design a workable GPS status reporting system.____

Table A.1

Summary of Survey Results Short Answer Questions

Response	1	2	3	4	5	6
Question 1.	1	1	7	92	1	N/A
2	31	9	56	33	4	29
3.	62 indicated civilian pilot ratings 40 indicated no civilian aviation experience or did not answer the question.					
4.	7	43	25	23	4	N/A
5.	4	84	14	N/A	N/A	N/A
6.	24	30	27	15	5	N/A
	Note: one person did not answer this question					
7.	13	45	19	19	6	N/A
8.	0	17	27	44	14	N/A
9.	2	45	31	21	3	N/A
10.	35	45	10	8	4	N/A
11.	39	41	18	3	1	N/A

Question 12. The following is a summary of the written comments that specifically address the design of a GPS status reporting system. Emphasis and word choice are the respondents.

1. A "worst case" coverage could be provided for a given area for the next 6 hours. The pilot would expect better than the number published.

2. Make it as simple for the flight crew as possible--don't look up stuff in FLIP/tables/charts (there's already a paperwork excess!).

3. As in all such matters-- "Keep it simple!"

4. Any way receivers could reflect status of individual satellites would be ideal.

5. The system should be fully automated with <u>no</u> pilot compensation necessary. If you want a good example of friendly operation, take a look at the Honeywell LASPRNAV. In this day of microcomputers, having to pull out books or refer to NOTAMs and charts is taking a giant step backward.

6. Design a receiver to display both horizontal and altitude accuracy.

7. The basics of timely status ,simple effectiveness (by area or route) and immediate availability are the ultimate grading criteria for pilots.

8. Don't make it too complicated. <u>Keep it simple!!</u>

9. Need something in the cockpit (idiot lights) to tell when only horizontal guidance is available, when CEP is below specified levels and when the information is totally unusable.

10. Put GPS satellite coverage on a CRT similar to weather satellite coverage areas.

11. I would rather see a database system showing which areas will not receive coverage. As an aircrew member, we have time restrictions on us and time spent looking in a book to see if we have coverages is less time for other mission planning duties. NOTAM system OK if it tells us which areas are affected rather than referring us to a booklet. Also would be nice to have it incorporated into ATIS.

12. System should directly provide useability of network and not require a user to calculate degradation to determine useability.

13. Don't worry too much if it isn't working. Somehow we will survive.

14. I don't care which satellite is out, just which areas. If I lose altitude no biggie, just let me know.

15. Use NOTAM system already in place.

16. Have a flag on the aircraft unit to display status.

17. To the largest extent possible, computerization of GPS status reporting should be employed. The days of hardcopy NOTAMs and flip documents is quickly coming to an end. Let's not be behind the times as soon as the system is deployed. High technology is an appropriate solution. Let's not build a dinosaur.

18. Could a base GPS frequency monitor check satellite transmission status and automatically trigger GPS degrade info rather than a large integrated net?

19. Computer based info is the best way to go but be sure there is a back-up which can be queried when your local display is "off the air".

20. Keep it simple and usable in remote areas.

21. Make status available via radio contact to ARTCC or other ground or air contact points.

22. My concern about the NOTAM system and possibly the database system is for 8-10 hour over-water flights where GPS will be most important.

23. A NOTAM system for degraded coverage <u>must</u> make it absolutely clear to the pilot whether or not he can file to and fly an approach. In my opinion, referring pilots to an additional flip book to determine if a NAVAID is acceptable for use makes the answer subject to interpretation and has an increased effect on the safety factor.

24. Computers are fine, however, back-up manual system needs to be available.

25. Most of all keep the procedures as simple as possible!

26. Should be very easy to use so average "crew dog" can do it without much hassle.

27. Maybe have varying degrees of degradation-- instead of "OK" vs "degraded", have "OK", "marginal" and "degraded". Have a 2 criteria display--3 D position and 2 D position.

APPENDIX B

US SAMPLE POINTS

MAP NO.	CITY	STATE	VOR	LAT/LONG	CRITERIA
1	ALBANY	NY	ALB	4245N/7348W	2c
2	ALBUQUERQUE	NM	ABQ	3503N/10649W	1c
3	AMARILLO	TX	AMA	3517N/10138W	2c
4	ARCATA	CA	FOT	4040N/12414W	3a
5	ATLANTA	GA	ATL	3338N/8626W	1c
6	ATLANTIC CITY	NJ	ACY	3927N/7435W	2a
7	BANGOR	ME	BGR	4450N/6852W	2a
8	BATTLE MTN	NV	BAM	4034N/11655W	3d
9	BELLINGHAM	WA	BLI	4757N/12235W	3a
10	BILLINGS	MT	BIL	4548N/10837W	2c
11	BIRMINGHAM	AL	VUZ	3340N/8654W	2c
12	BISMARK	ND	DIK	4646N/10040W	2c
13	BOISE CITY	ID	BOI	4333N/11611W	2c
14	BOSTON	MA	BOS	4221N/7060W	1a
15	BROWNSVILLE	TX	BRO	2555N/9722W	2a
16	BUFFALO	NY	BUF	4256N/7839W	1a
17	CASPER	WY	CPR	4205N/10617W	2c
18	CHARLESTON	WV	HVQ	3821N/8146W	2c
19	CHARLESTON	SC	CHS	3254N/8002W	2a
20	CHARLOTTE	NC	CLT	3512N/8057W	1c
21	CHARLOTTESVILL	VA	GVE	3801N/7809W	2c
22	CHEYENNE	WY	CYS	4113N/10446W	3c
23	CHICAGO	IL	JOT	4133N/8819W	1a
24	CLEVELAND	OH	DJB	4121N/8210W	1a
25	COLUMBUS	OH	APE	4009N/8235W	1c
26	CONCORD	NH	ENE	4325N/7037W	3d
27	CORPUS CHRISTI	TX	CRP	2754N/9727W	2a
28	DALLAS	TX	DFW	3252N/9702W	1c
29	DAYTONA BEACH	FL	OMN	2918N/8107W	2a
30	DENVER	CO	DEN	3948N/10453W	1c
31	DES MOINES	IA	DSM	4126N/9339W	2c
32	DETROIT	MI	CRL	4203N/8327W	1a
33	DULUTH	MN	DLH	4648N/9212W	2a
34	EL PASO	TX	ELP	3149N/10617W	1b
35	EUGENE	OR	EUG	4407N/12313W	2c
36	FRESNO	CA	RPI	3653N/11948W	2c
37	GLASGOW	MT	GGW	4813N/10637W	3c
38	GLENDALE	UT	BCE	3741N/11218W	3c
39	GOODLAND	KS	GLD	3923N/10141W	3c
40	GRAND FORKS	ND	GFK	4757N/9711W	2b
41	GRAND JUNCTION	CO	JNC	3904N/10847W	3c
42	GREAT FALLS	MT	GTF	4727N/11125W	2b
43	GREEN BAY	WI	GRB	4433N/8812W	2a
44	HARRISBURG	PA	HAR	4014N/7701W	2c
45	HARTFORD	CN	HFD	4138N/7233W	2c

US SAMPLE POINTS (cont)

MAP NO.	CITY	STATE	VOR	LAT/LONG	CRITERIA
46	HOUSTON	TX	HUB	2939N/9517W	1a
47	INDIANAPOLIS	IN	VPH	3949N/8622W	1c
48	JACKSON	MS	JAN	3230N/9010W	2a
49	JACKSONVILLE	FL	JAX	3020N/8131W	1a
50	KANSAS CITY	MO	MKC	3917N/9435W	1c
51	LAS VEGAS	NV	LAS	3539N/10508W	2c
52	LITTLE ROCK	AR	LIT	3441N/9211W	2c
53	LOS ANGELES	CA	LAX	3356N/11826W	1a
54	LOUISVILLE	KY	IIU	3806N/8535W	1c
55	MARQUETTE	MI	SAW	4622N/8723W	3b
56	MEDFORD	OR	OED	4229N/12255W	2a
57	MEMPHIS	TN	MEM	3504N/8959W	1c
58	MIAMI	FL	MIA	2558N/8028W	1a
59	MIDLAND	TX	INK	3152N/10315W	2c
60	MINNEAPOLIS	MN	MSP	4453N/9314W	1c
61	MINOT	ND	MOT	4816N10117W	3a
62	MOBILE	AL	SJI	3044N/8822W	2a
63	MONTEREY	CA	SNS	3640N/12136W	2a
64	NASHVILLE	TN	BNA	3607N/8641W	1c
65	NEW ORLEANS	LA	MSY	3002N/9010W	1a
66	NEW YORK	NY	JFK	4038N/7347W	1a
67	NORFOLK	VA	ORF	3653N/7612W	2a
68	NORTH PLATTE	NE	LBF	4103N/10045W	3c
69	OKLAHOMA CITY	OK	IRW	3521N/9736W	1c
70	OMAHA	NE	OMA	4110N/9544W	1c
71	PANAMA CITY	FL	PFN	3013N/8541W	2a
72	PHILADELPHIA	PA	ARD	4015N/7454W	1a
73	PHOENIX	AZ	SRP	3526N/11153W	1c
74	PITTSBURGH	PA	EWC	4049N/8012W	1c
75	PLATTSBURG	NY	PLB	4448N/7325W	3a
76	PORTLAND	OR	PDX	4545N/12235W	1c
77	PRESQUE ISLE	ME	PQI	4646N/6806W	3b
78	RAPID CITY	SD	RAP	4359N/10301W	3c
79	REDDING	CA	RBL	4006N/12214W	3a
80	RENO	NV	FMG	3932N/11939W	2c
81	SALT LAKE CITY	UT	SLC	4051N/11159W	2c
82	SAN ANTONIO	TX	SAT	2939N/9828W	1c
83	SAN DIEGO	CA	MZB	3247N/11713W	1a
84	SAN FRANCISCO	CA	SFO	3737N/12222W	1a
85	SAVANNAH	GA	SAV	3210N/8107W	2a
86	SEATLE	WA	SEA	4726N/12218W	1a
87	SHREVEPORT	LA	SHV	3246N/9349W	2c
88	SIOUX FALLS	SD	FSD	4339N/9646W	2c
89	SPOKANE	WA	GEG	4734N/11738W	2b
90	SPRINGFIELD	IL	CAP	3953N/8937W	2c

US SAMPLE POINTS (cont)

MAP NO.	CITY	STATE	VOR	LAT/LONG	CRITERIA
91	ST LOUIS	MO	STL	3852N/9029W	1c
92	ST PETERSBURG	FL	PIE	2754N/8241W	2a
93	TUBA CITY	AZ	TBC	3607N/11116W	3c
94	TUCSON	AZ	TUS	3206N/11055W	1b
95	WACO	TX	ACT	3140N/9716W	2d
96	WASHINGTON DC	DC	OTT	3842N/7645W	1a
97	WICHITA	KS	ICT	3745N/9735W	2c
98	WILMINGTON	NC	ILM	3421N/7752W	2a
99	YELOWSTONE	WY	DBS	4405N/11212W	3c
100	YUMA	AZ	BZA	3246N/11436W	3b

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Vita

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The purpose of this study was to design a status reporting system for NAVSTAR GPS. A systems engineering approach was used for the full satellite constellation with fully functioning user equipment. The recommended system consists of three main elements: a database, a status transmission mechanism, and microcomputer software. The database proposed has two tiers and is maintained in real-time as the operational constellation changes. The first tier contains the orbital ephemeris of the active constellation. The second tier consists of areas and associated times of degraded coverage.

Two methods of initial transmission of the status information are identified. The Notices to Airmen (NOTAM) system that currently exists is one primary transmission system. The other recommended initial link in the transmission process is electronic mail. Further dissemination by appropriate agencies using a variety of transmission methods is also outlined.

The final element of the system is software that can run on microcomputers. This software would allow users with special requirements to compute degraded coverage from the ephemeris data using assumptions and parameters different from those used in producing the second tier of the database.

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